B. Atlantic Herring WP-1

June 12, 2018

SARC 65

DRAFT Atlantic Herring Assessment for 2018

By the

Atlantic Herring SAW Working Group

B. Atlantic herring

The SARC 65 Atlantic Herring Working Group conducted a Data meeting (February 6-7, 2018) and a Model meeting (May 2-4, 2018) in the development of this assessment. The SAW/SARC Herring Working Group members are:

Jon Deroba – NEFSC Population Dynamics (Assessment lead)

John Manderson – NEFSC Coop Research

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Matt Cieri –ME DMR

Ashleen Benson – Landmark Fisheries

Gary Shepherd – NEFSC Population Dynamics (WG-Chair)

Executive Summary

TOR B1. Estimate catch from all sources including landings and discards. Describe the spatial and temporal distribution of landings, discards, and fishing effort. Characterize uncertainty in these sources of data. Comment on other data sources that were considered but were not included.

US catches were developed for the years 1965-2017 and were a sum of landings and self-reported discards. Discards have only been available since 1996, but were generally less than 1% of landings. Consequently, discards do not represent a significant source of mortality and a lack of historical discards is not considered problematic for the assessment. US catches were developed separately for fixed and mobile gear types. Catches from the New Brunswick, Canada, weir fishery were provided for the years 1965-2017 and were added to the US fixed gear catches for the purposes of assessment.

Total catches during 1964-2017 ranged from 44,613 mt in 1983 to 477,767 mt in 1968. Total catches during the past five years ranged from 50,250 mt in 2017 to 101,622 mt in 2013 and averaged 79,206 mt. Mobile gear catches have been the dominant gear type since about 1995.

TOR B2. Present the survey data being used in the assessment (e.g., regional indices of abundance, recruitment, state surveys, age-length data, food habits, etc.). Characterize the uncertainty and any bias in these sources of data.

Abundances (i.e., arithmetic mean numbers per tow) from the NMFS spring, fall, and summer shrimp bottom trawl surveys were used in the assessment model along with annual coefficients of variation and age composition when they were available. The trawl door used on the spring and fall surveys changed in 1985 and likely altered the catchability of the survey gear. Consequently, the spring and fall surveys were split into two time series between 1984 and 1985, and these were treated as separate indices in assessment models. The spring and fall surveys also used a different vessel (i.e., the Bigelow) beginning in 2009, and so these surveys were split again to account for this vessel change. Ultimately, the spring and fall surveys had three time stanzas: 1965-1984, 1985-2008, 2009-2017.

An acoustic index collected during the NMFS fall bottom trawl survey was also used as an index of herring abundance. This survey has no age composition data and so selectivity was knife-edged at age-3.

Several other indices of abundance were considered, but not used in the final assessment model. These indices included: NMFS winter survey, Massachusetts state surveys (spring and fall), joint Maine/New Hampshire state surveys (spring and fall), and an index based on food habits data.

TOR B3. Estimate consumption of herring, at various life stages. Characterize the uncertainty of the consumption estimates. Address whether herring distribution has been affected by environmental changes.

Fish food habits data from NEFSC bottom trawl surveys were evaluated for 12 herring predators. From these data, diet composition of herring, per capita consumption, and the amount of herring removed by the 12 predators were calculated. Combined with abundance estimates of these predators, herring consumption was summed across all predators as total herring consumption. Annual removal of herring amounted to 10s to 100s of thousands of mt by these predators. Annual removal ranged from 32,700mt in 1983 to 390,000mt in 2008. Amount of deaths due to input natural mortality in the stock assessment were compared to the estimates of predatory consumption as a general check of scale.

TOR B4. Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and estimate their uncertainty. Incorporate ecosystem information from TOR B3 into the assessment model, as appropriate. Include retrospective analyses (both historical and within -model) to allow a comparison with previous assessment results and projections, and to examine model fit.

The base ASAP model made structural changes to the previous assessment (e.g., M, selectivity), included new index time series, and re-evaluated some other relatively minor issues (e.g., weak likelihood penalties). Of particular importance, however, was a change to M. Natural mortality in recent assessments varied by time and age, with values based on a combination of the Hoenig and Lorenzen methods (Hoenig 1983; Lorenzen 1996). In 2012, the natural mortality rates during 1996-2011 were increased from these base rates by 50% to resolve a retrospective pattern and to ensure that the amount of herring deaths due to input M were consistent with observed increases in estimated consumption of herring. In 2015, a retrospective pattern re-emerged and implied levels of consumption were no longer consistent with estimated consumption. Thus, assumptions about time- and age-varying M were reevaluated as part of this assessment. Ultimately, M equaled 0.35 for all years and ages in this assessment.

The base ASAP model estimated SSB in 2017 to be 141,473 mt, with SSB ranging from a minimum of 53,084 mt (1982) to a maximum of 1,352,700 mt (1967) over the entire time series. The base ASAP model estimated total January 1 biomass in 2017 to be 239,470 mt, ranging from a minimum of 169,860 mt (1982) to a maximum of 2,035,800 mt (1967) over the entire time series.

No common age is fully selected in both the mobile and fixed gear fishery. Consequently, the average F between ages 7 and 8 was used for reporting results related to fishing mortality (F_{7-8}), and this includes reference points. These ages are fully selected by the mobile gear fishery, which has accounted for most of the landings in recent years. F_{7-8} in 2017 equaled 0.45. The all-time low of 0.13 occurred in 1965. The all-time high of 1.04 occurred in 1975.

Age-1 recruitment has been below average since 2013. The all-time high of 1.4 billion fish occurred in 1971. The estimates in 2009 and 2012 are still estimated to be relatively strong cohorts, as in previous assessments. The all-time low of 1.7 million fish occurred in 2016, and the second lowest of 3.9 million fish occurred in 2017. Four of the six lowest recruitment estimates have occurred since 2013 (2013, 2015, 2016, 2017).

The internal relative retrospective pattern suggested consistent overestimation of SSB with Mohn's Rho = 0.15, and underestimation of F_{7-8} with Mohn's Rho = -0.11. The retrospective pattern for recruitment at age 1 was characterized by both positive and negative peels. The presence of the retrospective pattern was sensitive to the indices of abundance used in the model. The retrospective pattern was not severe enough, however, to warrant an adjustment for stock status determination or projections. Estimating catchability separately for the Bigelow years in 2009-2017 may also be aliasing other causes of the retrospective pattern, and so future herring assessments may have worsening retrospective patterns.

TOR B5. State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY},

$B_{THRESHOLD}$, F_{MSY} and MSY) and provide estimates of their uncertainty. If analytic model-based estimates are unavailable, consider recommending alternative measurable proxies for BRPs. Comment on the scientific adequacy of existing BRPs and the "new" (i.e., updated, redefined, or alternative) BRPs.

The existing MSY reference points were based on the fit of a Beverton-Holt stock-recruitment relationship, estimated internally to the ASAP model, and inputs (e.g., weights-at-age, natural mortality) from the terminal year of the assessment (i.e., 2014). Point estimates of the MSY BRPs equaled: MSY = 77,247 mt, F_{MSY} = 0.24, and SSB_{MSY} = 311,145 mt.

No stock-recruit relationship was able to be estimated in this assessment, therefore $F_{40\%}$ was used as a proxy for F_{MSY} and long-term projections were used to derive other MSY BRP proxies. F_{MSY} proxy = 0.51, SSB_{MSY} proxy = 189,000 mt (½ SSB_{MSY} = 94,500 mt), and MSY proxy = 112,000 mt.

The existing MSY reference points were based on estimates of a Beverton-Holt stock-recruit curve fit internally to the ASAP model. The ability to estimate the stock-recruit curve seems to have deteriorated in this assessment, but the ability of previous models to estimate a stock-recruit curve has also been noted as tenuous. The newly proposed reference points no longer rely on a poorly estimated stock-recruit relationship.

TOR B6. Make a recommendation about what stock status appears to be based on the existing model (from previous peer reviewed accepted assessment) and based on a new model or model formulation developed for this peer review.

a. Update the existing model with new data and evaluate stock status (over fished and overfishing) with respect to the existing BRP estimates.

Given the Working Group's conclusion that MSY reference points based on the estimation of a stock-recruit curve were unjustified, and were likely unjustified in previous assessments, the existing BRPs are not meaningful. Similarly, evaluating stock status of the existing model with updated data to the existing MSY BRPs is not informative.

b. Then use the newly proposed model and evaluate stock status with respect to "new" BRPs and their estimates (from TOR B5).

The base ASAP model estimated $F_{7\text{-}8}$ in 2017 to be 0.45 and SSB in 2017 was 141,473 mt. Since the retrospective adjusted values do not fall outside of the confidence intervals of the base model estimates, no retrospective adjustment was warranted. A comparison of the base model values to the new MSY proxy reference points suggest that overfishing is not occurring and that the stock is not overfished. The error bars for $F_{7\text{-}8}$, however, included overfishing.

c. Include descriptions of stock status based on simple indicators/metrics.

The estimated numbers at age in 2017 indicate that the population is characterized by more age 6 fish than age 1 and age 2 combined. This result suggests a reliance on the ageing 2011 cohort (age 6 in 2017). If the estimated record low recruitments in recent years hold true, then the SSB is likely to remain relatively low and put the stock at relatively high risk of becoming overfished. Without improved recruitment, the probability of overfishing under recent catch levels is also likely relatively high.

TOR B7. Develop approaches and apply them to conduct stock projections.

a. Provide numerical annual projections (through 2021) and the statistical distribution (i.e., probability density function) of the catch at F_{MSY} or an F_{MSY} proxy (i.e. the overfishing level, OFL) (see Appendix to the SAW TORs). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass. Use a sensitivity analysis approach in which a range of assumptions about the most important uncertainties in the assessment are considered (e.g., terminal year abundance, variability in recruitment).

Short-term projections of future stock status were conducted based on the results of the base ASAP model. The projections did not account for any retrospective pattern because the Mohn's Rho adjusted values for stock status were within the 80% probability intervals of the 2017 point estimates of $F_{7\text{-}8}$ and SSB. If the Allowable Biological Catch (ABC) is fully utilized in 2018 (i.e., 111,000mt), then catch at F_{MSY} proxy in 2019=13,700mt, 2020=31,000mt, and 2021=55,700mt. If only half the ABC is utilized in 2018 (i.e., 55,000mt), then catch at F_{MSY} proxy in 2019=28,900mt, 2020=38,000mt, and 2021=59,400mt. As with the catches, future short-term stock status was also sensitive to the catch specified in 2018.

b. Comment on which projections seem most realistic. Consider the major uncertainties in the assessment as well as sensitivity of the projections to various assumptions. Identify reasonable projection parameters (recruitment, weight-at-age, retrospective adjustments, etc.) to use when setting specifications.

The Working Group agreed that the 2018 ABC of 111,000mt is unlikely to be fully utilized and that some lower value was more realistic, but that value is likely best determined by a technical group of the New England Fishery Management Council. The projections assumed that future recruitment will approach the mean for the time series (1965-2015). If recruitment continues to be below average, the projected catch increases may be overly optimistic.

c. Describe the stock's vulnerability (see "Appendix to the SARC TORs") to becoming overfished, and how this could affect the choice of ABC (or DEF, possibly even GH&I).

The unknown contributions of the Scotian Shelf (4WX), Gulf of Maine, and Georges Bank stocks can affect the stocks vulnerability to becoming overfished. The vulnerability of the stock has been demonstrated by the historical collapse of the Georges Bank component in the 1980s, which also demonstrated that the multiple spawning groups can be differentially impacted by fishing. Varying contributions from the Scotian Shelf (4WX) stock may also contribute to a retrospective pattern (see below).

In the short-term, the relatively poor recruitments in 2013-2017 will increase the vulnerability of the stock to becoming overfished. The 2016 and 2017 cohorts were imprecisely estimated and so estimates of these cohorts may change significantly in either direction in future assessments, and decisions should likely consider this uncertainty. Growth (i.e., weight at age) also continues to be relatively low when compared to the 1990s, and this seems to be a longer-term feature of the stock that also reduces production. The stock, however, seems to be capable of producing relatively large and small year classes regardless of growth, and so recruitment is likely the more significant driver of short-term vulnerability.

While this assessment had a retrospective pattern that did not warrant adjustments (i.e., via Mohn's Rho), the history of the Atlantic herring stock assessment suggests that resolutions to retrospective patterns are ephemeral, and so future herring assessments may have worsening retrospective patterns. Retrospective patterns are indicative of model misspecification, and this would increase the vulnerability of the stock to becoming overfished.

TOR B8. If possible, make a recommendation about whether there is a need to modify the current stock definition for future assessments.

Previous assessments concluded that there is likely sub-stock structure unaccounted for in the assessment, but that there is no ability to distinguish mixed survey and fishery catches to stock of origin. This lack of information on stock of origin precludes accounting for the sub-stock structure. An attempt was made to use an assessment model (Stock Synthesis) that accounted for stock structure on a coarse level (i.e., inside and outside of Gulf of Maine), but estimating area-specific recruitment and movement rates required unrealistic assumptions and the model generally performed poorly (e.g., poor convergence). The consequences of not accounting for stock structure are unclear, and therefore the need to modify the stock definition is also unclear. More certain, however, is that changing the stock definition and accounting for stock structure in the assessment is currently not possible. Continued research on the topic is warranted.

TOR B9. For any research recommendations listed in SARC and other recent peer reviewed assessment and review panel reports, review, evaluate and report on the status of those research recommendations. Identify new research recommendations.

Research recommendations from previous assessments were reviewed and progress on each updated and documented. Several new research recommendations were developed.

Management Summary and History

Fisheries Management

The Atlantic herring fishery in the Northeastern U.S. operates from Maine to Cape Hatteras, North Carolina and from inshore to offshore waters on the edge of the continental shelf. The herring fishery uses predominantly single and paired mid-water trawl, bottom trawl, purse seine, and to a lesser extent, gillnet gear throughout the entire range. Herring is used primarily in the U.S. as bait for the American lobster and tuna fisheries, but is also frozen whole and canned for human consumption. Herring is managed in federal waters by the New England Fishery Management Council (NEFMC), and in state waters by the Atlantic States Marine Fisheries Commission (ASMFC). Individual states may set different regulations, such as possession/landing restrictions or spawning area closures. If state regulations differ from Federal regulations, herring permit holders must adhere to the more restrictive regulations.

Atlantic herring stocks were first managed in 1972 through the International Commission for the Northwest Atlantic Fisheries (ICNAF). ICNAF regulated the international fishery until the United States withdrew from the organization in 1976 with the passage of the Magnuson Fishery Conservation and Management Act (MSA). The Atlantic Herring Fishery Management Plan (FMP) was one of the first plans developed by the NEFMC, approved in 1978. In 1982, NMFS withdrew the Federal Herring FMP because of conflicts between state and federal regulations, and catch quotas for adult herring in the Gulf of Maine were not enforced in state waters. In the absence of a Federal FMP, Atlantic herring was placed on the prohibited species list, thereby eliminating directed fisheries by foreign nationals or joint ventures in the EEZ and requiring any herring bycatch by such vessels to be discarded.

While directed fishing for Atlantic herring was prohibited in Federal waters in 1983, the herring fishery in State waters was managed through an agreement among the States of Maine, New Hampshire, Massachusetts, and Rhode Island. The final draft of the “Interstate Herring Management Plan of Maine, New Hampshire, Massachusetts, and Rhode Island” was adopted in late 1983 and formally recognized by the Atlantic States Marine Fisheries Commission (ASMFC) in 1987. The primary management tool was spawning closures, but as the size of the resource and fishery grew, this measure was not sufficient. The ASMFC developed the Atlantic Herring Fishery Management Plan in 1993 to address the growth of the herring resource, formalize the allocation process, and lay the foundation for a joint ASMFC-NEFMC management plan.

The New England Council's Herring FMP became effective on January 10, 2001 and included administrative and management measures to ensure effective and sustainable management of the herring resource. The FMP establishes Total Allowable Catches (TACs, now referred to as sub-ACLs, or annual catch limits) for each of four management areas as the primary control on fishing mortality (see Figure B- **1** for current herring management areas). ASMFC adopted Amendment 2 to complement the federal Amendment 1 measures.

The federal FMP has been improved by several subsequent Amendment and Framework actions over the years (Amendments 1-7 and Frameworks 1-4). These actions are described briefly in the bullets below.

- **Framework Adjustment 1 (effective 2002)** set measures for fishing year 2002 and split the TAC for Area 1A into two seasonal components to prevent an early closure of the fishery in 1A.
- **Amendment 1 (effective 200**7) was developed to improve resource conservation, address new scientific information to the extent possible, minimize the potential for excess harvesting capacity in the fishery, and provide a platform to promote long-term economic stability for harvesters, processors, and fishing communities. A limited access program was implemented, management boundaries were adjusted, a seasonal purse seine/fixed gear only area was established for all of Area 1A from June-September, a three-year specifications process was developed, as well as several other adjustments to the management program.
- **Amendment 2 (effective 2008)** was part of an omnibus amendment developed by NMFS to ensure that all FMPs of the Northeast Region comply with the Standardized Bycatch Reporting Methodology (SBRM) requirements of the MSA.
- **Amendment 4 (effective in 2011)** implemented a process for establishing annual catch limits (ACLs) and accountability measures (AMs) in the herring fishery and brought the Herring FMP into compliance with the reauthorized MSA.

- **Framework 2 (effective 2014)** Framework 2 set catch specifications for the herring fishery for the 2013–2015 fishing years and established seasonal splits for management areas 1A and 1B as recommended to NMFS by the Council, and other measures related to specifications.
- **Framework 3 (effective 2014**) to establish a process for setting river herring (alewife and blueback) and shad (American and hickory) catch caps for the herring fishery, including allocations for 2014 and 2015 fishing years.
- **Amendment 5 (effective 2014) to:** Improve the collection of real-time, accurate catch information; enhance the monitoring and sampling of catch at-sea; and address bycatch issues through responsible management by revising several program provisions, expanding vessel requirements to maximize observers' ability to sample catch-at-sea, minimize discarding of unsampled catch, addressing incidental catch of RH/S and revising criteria for MWT vessels in groundfish closed areas.
- **Framework 4 (effective 2016)** to further enhance catch monitoring and address discarding in the herring fishery by establishing requirements for herring dealers and restrictions on vessels when they release catch before it can be sampled by at-sea-observers (known as slippage).
- **Amendment 6 (effective 2016)** was part of an omnibus amendment to establish standards of precision for bycatch estimation for all Northeast fisheries (SBRM Amendment).
- **Amendment 3 (effective 2018)** was part of an omnibus amendment to all New England Council FMPs to address Essential Fish Habitat (EFH) consistent with the MSA.
- **Amendment 7 (scheduled 2018)** to allow the Councils to implement industry-funded monitoring above levels required by SBRM Amendment, including specific measures for an industry funded monitoring program for the herring fishery.
- **Amendment 8 (scheduled 2019)** to implement an ABC control rule and consider measures to address potential localized depletion and user conflicts in the herring fishery.

In general, the herring fishery is managed by a stock-wide annual catch limit (ACL) that is allocated to four distinct management areas (sub-ACLs, also known as management area quotas). The fishery allocations or specifications stem from the sub-ACLs and are currently set every three years. Due to the spatial structure of the Atlantic herring stock complex (multiple stock components that separate to spawn and mix during other times of the year), the total annual catch limit for Atlantic herring (stock-wide ACL/OY) is divided and assigned as sub-ACLs to four management areas (Figure B- **1**). The best available information is used about the proportion of each spawning component of the Atlantic herring stock complex in each area/season and minimizing the risk of overfishing an individual spawning component to the extent practicable.

Other species are caught incidentally in the directed herring fishery. The species composition varies based on gear type, year, season, and area, but some of the species caught include: Atlantic mackerel, haddock, river herring (alewife and blueback herring), shad (American shad and hickory shad), whiting, and spiny dogfish. Due to the high-volume nature of the Atlantic herring fishery, non-target species are often retained once the fish are brought on board and sometimes sold as part of the overall catch if they are not separated. The herring fishery has been allocated a sub-ACL of Georges Bank haddock, and there are also bycatch caps for river herring/shad. The herring fishery is subject to accountability measures for both caps and directed herring fishing is prohibited in specific areas for the remainder of the fishing year when 95% of a bycatch cap is estimated to be caught.

The Atlantic herring stock wide ACL and management area sub-ACLs are tracked/ monitored based on the *total catch – landings and discards*, which is provided and required by herring vessels through the vessel monitoring system (VMS) catch reports and vessel trip reports (VTRs) as well as through Federal/state dealer data. Atlantic herring catch has been variable in recent years, but on average about 90,000 mt for the last decade or so (Table B1- 1). However, the quota allocated to the fishery (stock wide ACL) has decreased during this time. Consequently, the Atlantic herring fishery has become more fully used in recent years, with some exceptions. These exceptions could be related to resource abundance, but there are a variety of factors that have likely caused under harvests of catch limits, including management measures in the plan.

For example, in 2015 the fishery in Area 3 became constrained by the Georges Bank Haddock catch cap accountability measure. Area 3 closed to midwater trawl (MWT) gear during the season, and under 75% of the herring quota was harvested in that area before the haddock cap was reached and directed fishing with MWT gear was prohibited. This closure also had impacts on 2016 catch in Area 3 because the restriction is based on the multispecies fishing year, which is May 1 through April 30. Therefore, directed herring fishing in Area 3 was also prohibited in January 1 – April 30 in 2016, making it more difficult for the fishery to harvest the full allocation in Area 3 in the remaining months of the year. Therefore, the utilization of Area 3 herring quota was potentially impacted by the haddock catch cap in both 2015 and 2016.

In addition, there are other measures in place that have the potential to limit herring landings, especially when they are combined, potentially having cumulative impacts that limit flexibility and reduce the ability for the fishery to harvest the full TAC in each area. For example, there are various seasonal restrictions that limit when vessels can fish in certain areas. Table B- **1** summarizes some of these restrictions by month. Despite these restrictions, the sub-ACL for Area 1A and 1B have been fully harvested in most years. More recently, ASMFC has also placed restrictions on Area 1A that has further reduced flexibility and impacted fishing behavior in that area. In 2018 Addendum 1 to Amendment 3 of the ASMFC plan implemented weekly catch limits and restrictions on carrier vessels in Area 1A, in addition to the days-out measures that control the number of potential harvesting days per week. In 2018, the full Area 1A sub-ACL was not harvested, in part potentially due to the weekly catch limits, as well as implementation of spawning closures that prevent herring fishing by any gear type in different areas within Area 1A.

While bycatch caps have not been reached in many cases, there have certainly been a number of years that the fleet has approached them, and adjusted fishing behavior mid-season to avoid closures. As the fleet approaches the cap, avoidance behaviors have been observed such as moving to new areas and that can impact full utilization of the herring sub-ACLs. In addition to the example explained above for the haddock cap in 2015 and 2016, fishing behavior was impacted in 2017 around Cape Cod when the RH/S cap reached about 80%, vessels voluntarily avoided that area for the remainder of the fishing year to avoid exceeding the cap. Furthermore, fishing behavior and ability to harvest sub-ACLs was definitely impacted in 2018 when the RH/S cap was reached in March closing the MWT herring fishery in all SNE/MA waters. At that time only 20% of the Area 2 herring sub-ACL has been harvested.

In addition to bycatch measures that can impose in-season restrictions on directed herring fishing, the federal herring plan also includes several measures that impose seasonal restrictions for other purposes. For example, Area 1B is closed every year from January 1 through April 30, primarily to provide more herring landings when it is needed most for the bait market, late spring through summer. This quota is a small fraction of the overall herring catch, under 5%, but seasonal closures can limit flexibility and if the fish are not in that area during other months when the area is open, it can potentially impact the ability to harvest the sub-ACL for that area. Similarly, Area1A is closed to all herring fishing in January 1 through May 30, and only open to purse seine gear June 1 – September 30. While the Area 1A sub-ACL is usually fully harvested, these seasonal restrictions, especially when combined with spawning closures imposed by ASMFC, can limit flexibility and potentially impact the ability of the fishery to harvest the full sub-ACL in that area.

Another measure that may also make it more difficult to fully harvest sub-ACLs is the requirement to carry an at-sea observer if a vessel wants to fish in a groundfish closed area. Amendment 5 to the Herring FMP allowed midwater trawl vessels to fish in Closed Areas is a fishery observer is onboard. If observers are not available, herring vessels are prohibited from fishing in those areas (Closed Areas 1 and II). If herring is more concentrated in groundfish closed areas in a particular year or season, and vessels are unable to get observers, it may be more difficult to harvest the Area 3 sub-ACL since those areas cover a relatively large portion of Area 3 where herring are typically found. While some of these restrictions and closed areas have recently changed under the Omnibus Habitat Amendment 2, many of the requirements for herring vessels to carry observers in groundfish closed areas remain the same.

Finally, many herring vessels are active in other fisheries so in some cases, effort in other fisheries can impact when and how much herring fishing occurs during a fishing year. For example, if squid fishing or mackerel fishing is productive, some vessels that have permits in those fisheries will decide to prosecute those fisheries that often have higher revenues and prices. Conditions change every year, and if a herring sub-ACL is not harvested in a particular year, that may not be related to herring resource conditions or herring management restrictions; it is possible that availability or market conditions in other fisheries drives herring fishing activity, at least partially. If herring vessels are focused in other fisheries, i.e. mackerel or squid, herring fishing patterns can be impacted. In summary, herring management is complex, and trends in catch alone may not be reflective of resource conditions. If sub-ACLs are not fully harvested it can be related to resource availability, but there are a web of management measures in place that can inhibit herring fishing activity and full utilization of sub-ACLs.

x = represents no herring fishing

y = represents no midwater trawl gear permitted

z = possible spawning closures, restricts all herring fishing, all gear types

		Sub-Area			
		1A	**1B**	**2**	**3**
Month	**1**	**x**	**x**		
	2	**x**	**x**		
	3	**x**	**x**		
	4	**x**	**x**		
	5	**x**			
	6	**y**			
	7	**y**			
	8	**y, z**			
	9	**y, z**			
	10	**z**			
	11				
	12				

Table B- 1 Summary of spatial and seasonal restrictions that are in place in the Atlantic herring fishery (both NEFMC and ASMFC actions) (Source: Manderson and Sarro (in prep.) Fishing industry perspectives on socio-ecological factors driving Atlantic Mackerel landings in US waters)

Figure B- 1 Atlantic Herring Fishery Management Areas

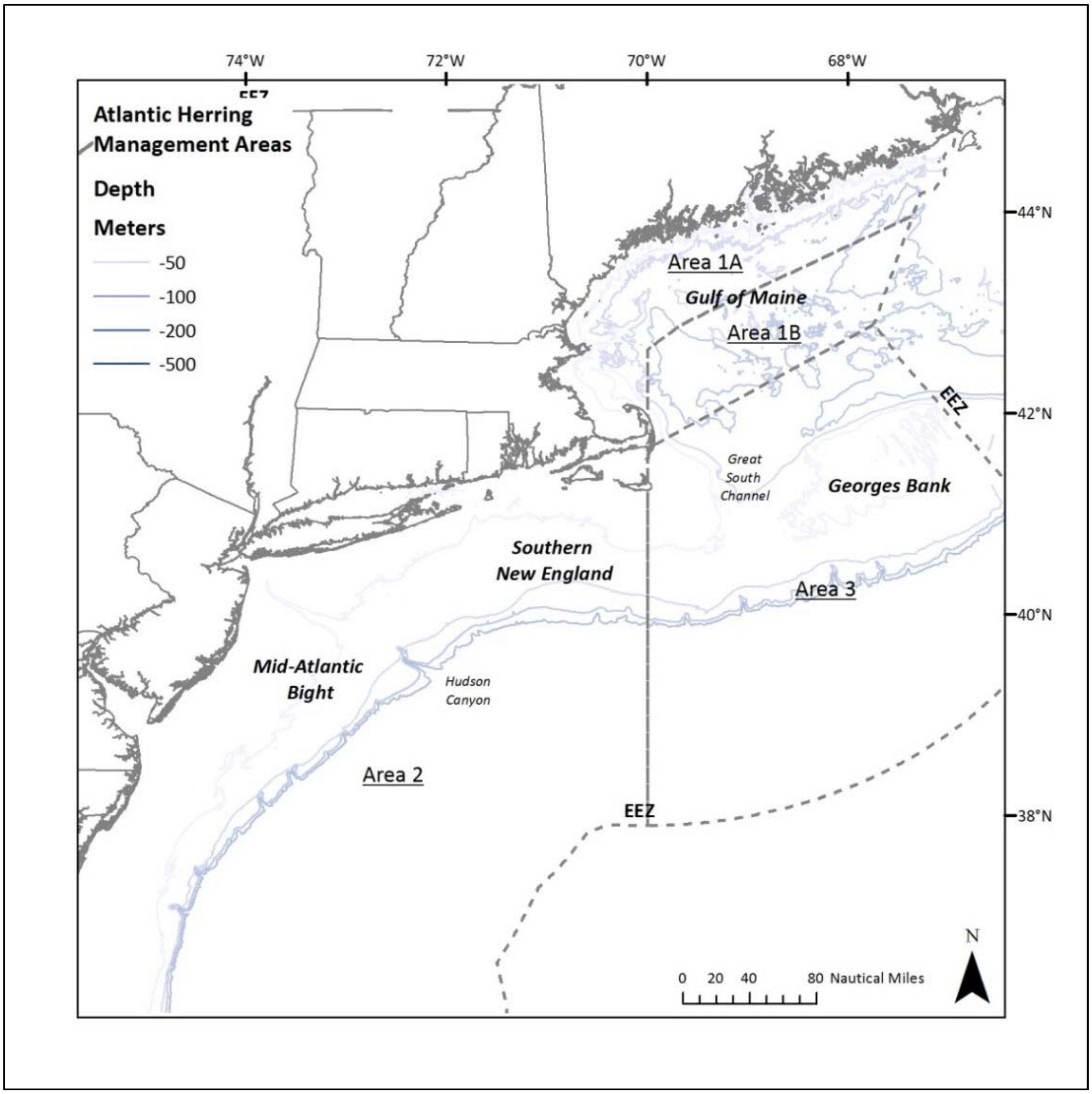
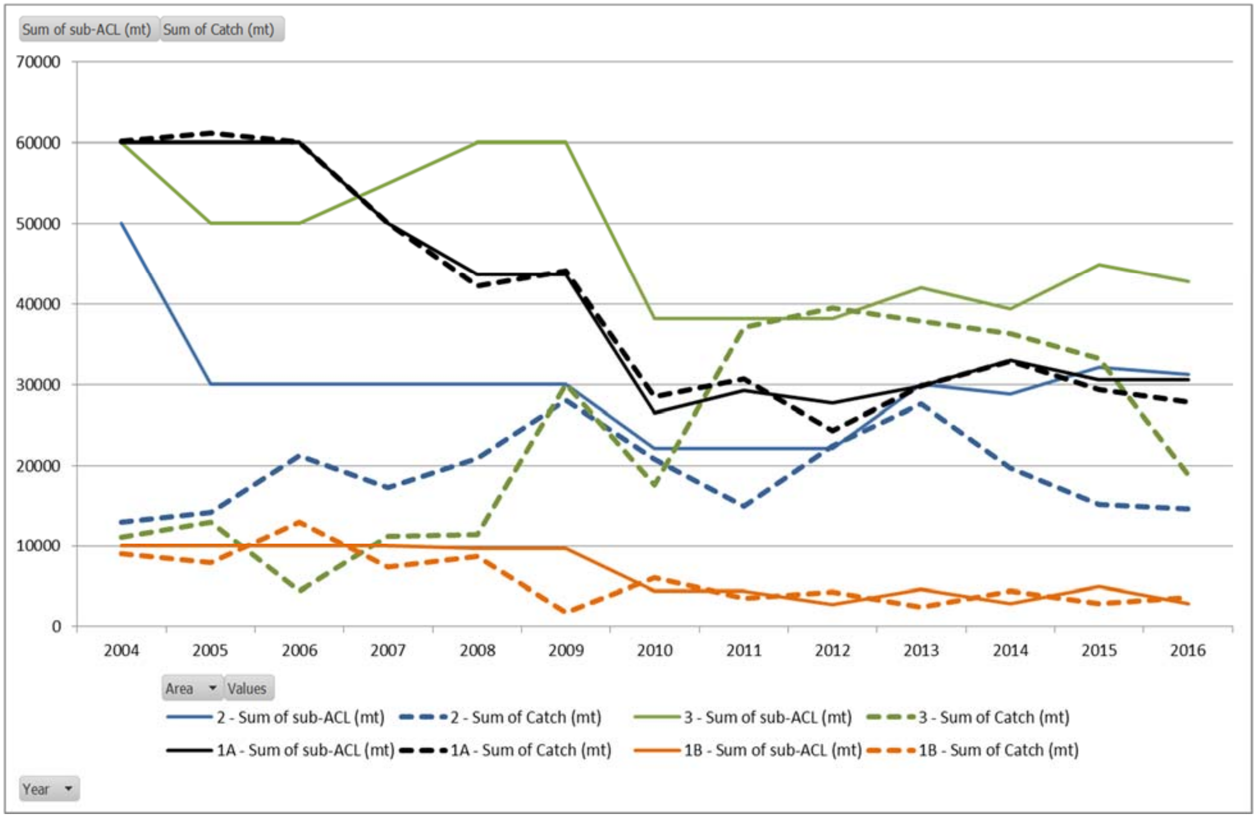


Figure B- 2 Atlantic herring sub-ACLs (solid lines) and estimated catch (dashed lines) by year and management area, 2004-2016



TOR B1: *Estimate catch from all sources including landings and discards. Describe the spatial and temporal distribution of landings, discards and fishing effort. Characterize uncertainty in these sources of data. Comment on other data sources that were considered but were not included.*

Data from the United States

The catch data used to develop the US herring catch at age for 1965 to 2017 comes from a combination of NMFS Dealer reports and Vessel Trip Reports (VTR), NAFO reports, DFO Canada, Maine DMR, and other state landings reports. The reported catch is a sum of landings and self-reported discards, but discard estimates were not available in all years (Table B1- 1; Table B1- 2). Observed discards, however, were generally less than 1% of landings and do not represent a significant source of mortality (Table B1- 2; Wigley et al. 2011). Consequently, a lack of historical estimates of discards is not considered problematic for stock assessments. When data availability permitted, all the calculations used to produce the catch at age data below were done at the level of year, quarter, and gear type. Gear type was defined as either fixed or mobile gear. All trawl gears and purse seines were considered mobile, while all other gears (weirs, fyke nets, pound nets, etc.) were classified as fixed. These two aggregate gear types were used because biological data (e.g., lengths, ages, weights) were insufficient to do calculations on specific gear types. Weight-length relationships were similar between fixed and mobile gears, so data were combined for the gear types to estimate the parameters of this relationship. When no weight-length or length frequency data existed for a unique combination of year, quarter, and gear type, the calculations were then done at the level of year, semester (January-June or July-December), and gear type. Similarly, when no weight-length or length frequency data existed for a unique combination of year, semester, and gear type, the calculations were done at the level of year and gear type. Aggregations to the level of year and gear type were only necessary for 7 years for the fixed gear type (none for mobile gear). For the fixed gear type, no biological data were available in 15 years (1995, 1997, 2000, 2002-2005, 2008-2013, 2016-2017). US catch at age for the fixed gear type was consequently not developed in these years. Age-length keys were developed at the level of year, semester, and gear type. When an observed length had no corresponding age data, age samples for that length from the alternative gear type were used. Any remaining lengths with no corresponding age data were imputed based on a multinomial logistic model fit to the age observations at that length for the given year, semester, and gear type combination (Gerritsen et al., 2006). Data on sampling intensity is provided in Table B1- 3, Table B1- 4, and Table B1- 5.

The Working Group had concerns that the purse seine gear had a selectivity distinct from trawl gears. More specifically, that the purse seine length frequencies were sometimes bi-modal and generally caught some smaller fish than trawl gears (Figure B1- 1; Figure B1- 2). Combining purse seines and trawl gears into the aggregate mobile gear and not accounting for these selectivity differences in an assessment model may induce diagnostic issues (e.g., residual patterns, retrospective patterns), especially since there have been temporal changes in the composition of the catch coming from each gear type (Figure B1- 3). One way to address this concern would be to develop separate catch at age matrices for purse seines and trawls, but a purse seine specific catch at age matrix could not be developed in time for this assessment and it is not clear whether biological data would support such efforts. Consequently, the working group considered some assessment models with time-varying selectivity for the mobile gear fleet as a way to evaluate the necessity of distinguishing between purse seines and trawl gears. The models with time-varying selectivity suggested that modeling purse seines separately from trawls was not supported (see TOR B4 for details).

US catch at age calculations did not include any spatial element because adding this to the stratification scheme resulted in a large number of combinations with little or no biological data (Table B1- 4; Table B1- 5). The gear types are also confounded in space, with nearly all the fixed gear catch coming from the Gulf of Maine (Figure B1- 4). Furthermore, the length frequencies of catches from different gears in the same area are clearly different, while length frequencies from the same gear in different areas are similar (Figure B1- 5; Figure B1- 6); suggesting that accounting for gear type was necessary while spatial differences were relatively inconsequential.

Data from New Brunswick, Canada

Department of Fisheries and Oceans, Canada, personnel (Rabindra Singh) provided catch at age data for the New Brunswick (NB), Canada, weir fishery during 1965-2017 (Table B1- 6). The NB weir fishery uses the same gears as the US fixed gear fishery and have similar age compositions (NEFSC 2012). Furthermore, some US weir operations are located in close geographic proximity to the NB weir fishery. Consequently, the working group agreed that data from the NB weir fishery and the US fixed gear fishery should be combined for the assessment.

Data summaries and assessment inputs

Catch in the mobile gear fishery peaked in the late 1960s and early 70s, largely due to efforts from foreign fleets (Figure B1- 7). Catch in this fishery was relatively stable during the 2000s, and has accounted for most of the Atlantic herring catches in recent years although the contribution has declined for the last four years. Catch in the fixed gear fishery has been variable, but has been relatively low since the mid-1980s (Figure B1- 7).

The US mobile gear fishery catches a relatively broad range of ages and some strong cohorts can be seen for several years (Figure B1- 8; Table B1- 7). In contrast, the fixed gear fishery harvests almost exclusively age 2 herring (Figure B1- 9; Table B1- 8).

A single matrix of catch weights at age was estimated as the catch weighted mean weights at age among the strata used to develop the US catch at age matrices and ultimately among the mobile and fixed gear fisheries (Table B1- 9). Weights at age for spawning stock biomass were estimated as the mean weights at age from the mobile gear fishery in quarter three (i.e., July-September; Table B1- 10). This data was used because the mobile gear fishery is relatively well sampled in all years and quarter three is when herring typically begin spawning. January 1 weights at age were estimated by using a Rivard calculation (Rivard 1982) of the SSB weights at age (Table B1- 11). Any missing weights at age in each matrix were replaced by a time series average from one of three time stanzas: 1965-1985, 1986-1994, or 1995-2017. These three time stanzas were used to accommodate the temporal changes in herring growth, mostly evident for older aged herring (e.g., Figure B1- 10). Since herring beyond age 8 experience relatively little growth, weight at age 8 was used to characterize fish in the plus group (age 8+) in the model.

Maturity at age was developed using samples from commercial catches during quarter three (July to September). Fish caught during this time of year were used because they reflect the maturity condition of herring just prior to or during spawning, and therefore are best for calculations related to spawning stock biomass. Fish of both sexes were included. Fish of unknown maturity were removed from the analysis (codes 0 and 9 in the dataset). Immature fish were defined as those classified as immature I or immature II (codes 1 and 2, respectively in dataset) while all other fish were considered mature (3=ripe, 4=eyed, 5=ripe and running, 6=spent, 7=resting). The observed proportions mature at age from quarter three of each year were input to assessments and used in the calculation of SSB (Table B1- 12). Using predicted proportions at age from a generalized additive model fit to the annual observations was considered (NEFSC 2012), but sample sizes were generally considered large enough that such modeling to reduce the effect of measurement uncertainty was deemed unnecessary (Table B1-13). Microscopic verifications of the maturity classifications was conducted, as was an exploration of the consequences of possible spring or skipped spawning (Appendix B7).

Spatial distribution of fishing effort

The fishery tends to operate as expected given what is known about Atlantic herring migration patterns. In the winter, fishery landings tend to be more southerly than other times of year. As warming occurs through the spring and summer and herring migrate to the north, fishery landings occur more frequently throughout the Gulf of Maine. As fish separate into components to spawn in the fall, fishery landings span the Gulf of Maine and Georges Bank (Figure B1- 11). Also see:

http://noaa.maps.arcgis.com/apps/webappviewer/index.html?id=5d3a684fe2844eedb6beacf1169ca854

Other data sources discussed

The Northeast Fisheries Science Centers (NEFSC) Cooperative Research Branch's Study Fleet pilot program began field-testing data collection with electronic systems in late 2001. The Goals were to (1) to assemble a group of commercial fishermen to collect high resolution (haul-by-haul) self-reported data on catch, effort and environmental conditions during usual fishing operations, (2) develop and implement an electronic data collection system. The program was intended to ultimately provide stock assessment scientists with more precise and accurate fishery-dependent data and to improve the understanding of catch rates and species assemblages through examination of variables such as time of day, temperature, depth, tidal strength, and sediment type (Palmer et al 2007). The Fisheries Logbook and Data Recording Software (FLDRS) was established in 2006 as a product of this pilot work. FLDRS collects information at both the trip and haul level including detailed information of effort, catch and apportionment.

From 2006-2013 the number of vessels using FLDRS while participating in the commercial Atlantic herring fishery varied from 1-7. Most of these vessel participated in the small-mesh bottom trawl fishery off Rhode Island. In late 2014, through collaboration with the Pacific States Marine Fisheries Commission and with cooperation with the Massachusetts Division of Marine, Fisheries Cooperative Research staff deployed FLDRS on the midwater and paired midwater Atlantic herring fleet. This greatly increased the number vessels using FLDRS, the amount of data collected and expanded the spatial extent of coverage. In 2016, vessels reporting haul-by-haul using FLDRS accounted for >40% of the total landings. This and future information should be able address specific research and management questions.

A more detailed description of the program is an Appendix B6.

Table B1- 1 Atlantic herring landings (mt)

Year	US Fixed	New Brunswick Weir	US Mobile	US Fixed + NB Weir (mt)	Total
1965	36440	31682	58161	68122	126282
1966	23178	35602	162022	58780	220802
1967	17458	29928	258306	47386	305692
1968	24565	32111	421091	56676	477767
1969	9007	25643	362148	34650	396798
1970	4316	15070	302107	19386	321493
1971	5712	12136	327980	17848	345828
1972	22800	31893	225726	54693	280419
1973	7475	19053	247025	26528	273553
1974	7040	19020	203462	26060	229522
1975	11954	30816	190689	42770	233459
1976	35606	29207	79732	64813	144545
1977	26947	19973	56665	46920	103585
1978	20309	38842	52423	59151	111574
1979	47292	37828	33756	85120	118876
1980	42325	13526	57120	55851	112971
1981	58739	19080	26883	77819	104702
1982	15113	25963	29334	41076	70411
1983	3861	11383	29369	15244	44613
1984	471	8698	46189	9169	55358
1985	6036	27864	27316	33900	61216
1986	2120	27885	38100	30005	68104
1987	1986	27320	47971	29306	77277
1988	2598	33421	51019	36019	87038
1989	1761	44112	54082	45873	99954
1990	670	38778	54737	39448	94184
1991	2133	24574	78032	26707	104739
1992	3839	31968	88910	35807	124717
1993	2288	31572	74593	33860	108452
1994	539	22242	63161	22781	85943
1995	6	18248	106179	18254	124433
1996	631	15913	116788	16544	133332
1997	275	20551	123824	20826	144651
1998	4889	20092	103734	24981	128715
1999	653	18644	110200	19298	129497
2000	54	16830	109087	16884	125971
2001	27	20210	120548	20237	140785
2002	46	11874	93176	11920	105096
2003	152	9008	102320	9160	111480
2004	96	20685	94628	20781	115409
2005	68	13055	93670	13123	106793
2006	1007	12863	102994	13870	116864
2007	403	30944	81116	31347	112462
2008	31	6448	84650	6479	91129
2009	98	4031	103458	4129	107587
2010	1263	10958	67191	12221	79413
2011	422	3711	82022	4133	86155
2012	9	504	87162	513	87675
2013	9	6431	95182	6440	101622
2014	518	2149	92566	2667	95233
2015	738	146	80465	884	81350
2016	1208	4060	62307	5267	67574
2017	258	2103	47889	2361	50250

Table B1- 2 Atlantic herring discards (mt), landings (mt), and the ratio of the two quantities for the fixed and mobile fleets

Year	Discards (mt)		Landings (mt)		D/L	
	Fixed	**Mobile**	**Fixed**	**Mobile**	**Fixed**	**Mobile**
1996	13	131	666	116609	0.02	0.00
1997	29	225	342	123504	0.08	0.00
1998	7	188	4925	103503	0.00	0.00
1999	5	48	704	110096	0.01	0.00
2000	6	317	62	108756	0.10	0.00
2001	11	539	54	119971	0.21	0.00
2002	3	38	52	93129	0.07	0.00
2003	8	22	159	102284	0.05	0.00
2004	9	477	103	94136	0.08	0.01
2005	3	299	76	93359	0.03	0.00
2006	1	199	1029	102772	0.00	0.00
2007	3	52	418	81045	0.01	0.00
2008	3	526	41	84111	0.07	0.01
2009	2	460	158	102928	0.01	0.00
2010	33	230	1511	66673	0.02	0.00
2011	5	174	582	81683	0.01	0.00
2012	7	145	176	86843	0.04	0.00
2013	3	166	78	94944	0.04	0.00
2014	1	292	533	92259	0.00	0.00
2015	1	83	757	80363	0.00	0.00
2016	2	122	1253	62137	0.00	0.00
2017	0	74	274	47798	0.00	0.00

Table B1- 3 Number of commercial trips sampled for Atlantic herring biological data

	Number of Trips		
Year	**Fixed**	**Mobile**	**Total**
1965	353	13	366
1966	221	29	250
1967	241	66	307
1968	308	14	322
1969	300	25	325
1970	117	40	157
1971	103	91	194
1972	120	103	223
1973	95	69	164
1974	144	146	290
1975	154	131	285
1976	238	150	388
1977	248	106	354
1978	232	276	508
1979	559	121	680
1980	192	268	460
1981	352	100	452
1982	127	105	232
1983	62	134	196
1984	10	161	171
1985	54	88	142
1986	18	56	74
1987	21	79	100
1988	24	77	101
1989	29	68	97
1990	37	107	144
1991	24	99	123
1992	38	126	164
1993	32	125	157
1994	15	75	90
1995	0	124	124
1996	6	137	143
1997	0	213	213
1998	10	173	183
1999	3	206	209
2000	0	195	195
2001	2	214	216
2002	0	200	200
2003	0	155	155
2004	0	141	141
2005	0	186	186
2006	1	211	212
2007	1	147	148
2008	0	125	125
2009	0	123	123
2010	0	119	119
2011	0	119	119
2012	0	120	120
2013	0	132	132
2014	1	142	143
2015	2	119	121
2016	0	93	93
2017	0	103	103

Table B1- 4 Number of Atlantic herring length samples by fleet and spatial area

Year	# Length Samples		Total	# Length Samples		Total
	Fixed	Mobile		Gulf of Maine	Other	
1965	20671	715	21386	21386	0	21386
1966	11123	1401	12524	36766	19888	56654
1967	11410	12263	23673	27583	22156	49739
1968	16521	698	17219	36167	18944	55111
1969	14502	2910	17412	50050	30086	80136
1970	4171	20099	24270	34914	26580	61494
1971	7879	41157	49036	21537	44213	65750
1972	12945	33970	46915	35384	23685	59069
1973	4682	33633	38315	26913	27120	54033
1974	13340	45394	58734	37424	29368	66792
1975	14816	35026	49842	32797	31181	63978
1976	21267	31556	52823	43546	21457	65003
1977	23336	20257	43593	45443	11316	56759
1978	11574	15154	26728	44045	863	44908
1979	28815	8479	37294	37108	186	37294
1980	8867	19448	28315	28115	200	28315
1981	17433	6095	23528	23428	100	23528
1982	6327	6369	12696	12496	200	12696
1983	3100	7915	11015	11015	0	11015
1984	500	9595	10095	10095	0	10095
1985	2700	6288	8988	8888	100	8988
1986	896	3850	4746	4746	0	4746
1987	1050	5344	6394	6394	0	6394
1988	1200	5340	6540	6440	100	6540
1989	1450	4850	6300	6300	0	6300
1990	1847	6727	8574	8574	0	8574
1991	1200	6963	8163	8113	50	8163
1992	1900	9643	11543	11543	0	11543
1993	1671	6265	7936	7879	57	7936
1994	755	3717	4472	4072	400	4472
1995	0	6183	6183	5895	288	6183
1996	300	7181	7481	6483	998	7481
1997	0	10905	10905	8855	2050	10905
1998	500	8656	9156	5517	3639	9156
1999	150	10296	10446	9095	1351	10446
2000	0	9159	9159	6852	2307	9159
2001	100	10078	10178	6252	3926	10178
2002	0	9640	9640	7569	2071	9640
2003	0	7712	7712	4656	3056	7712
2004	0	7099	7099	4658	2441	7099
2005	0	9280	9280	5683	3597	9280
2006	50	11005	11055	5869	5186	11055
2007	45	7730	7775	4984	2791	7775
2008	0	6359	6359	3744	2615	6359
2009	0	6157	6157	3426	2731	6157
2010	0	6127	6127	2737	3390	6127
2011	0	6248	6248	3579	2669	6248
2012	0	6307	6307	2655	3652	6307
2013	0	6676	6676	2255	4421	6676
2014	50	7160	7210	3584	3626	7210
2015	89	5824	5913	3032	2881	5913
2016	0	4868	4868	2850	2018	4868
2017	0	5311	5311	3893	1418	5311

Table B1- 5 Number of Atlantic herring age samples by fleet and spatial area

Year	# Age Samples		Total	# Age Samples		Total
	Fixed	Mobile		Gulf of Maine	Other	
1965	2794	309	3103	3103	0	3103
1966	2337	481	2818	3862	1032	4894
1967	2250	1079	3329	3733	1190	4923
1968	2431	208	2639	3649	976	4625
1969	2149	392	2541	4185	1566	5751
1970	1173	1582	2755	3063	1444	4507
1971	1654	3248	4902	2982	2854	5836
1972	1521	2904	4425	3611	1516	5127
1973	940	2270	3210	2562	1396	3958
1974	1366	3251	4617	3329	1692	5021
1975	1848	2799	4647	3506	1973	5479
1976	1985	2632	4617	4135	1298	5433
1977	2070	2064	4134	4069	785	4854
1978	1272	2584	3856	5013	263	5276
1979	2178	1360	3538	3460	78	3538
1980	1285	2197	3482	3434	48	3482
1981	1370	1166	2536	2488	48	2536
1982	868	1339	2207	2105	102	2207
1983	385	1372	1757	1757	0	1757
1984	102	1971	2073	2073	0	2073
1985	344	1342	1686	1665	21	1686
1986	177	981	1158	1158	0	1158
1987	208	1384	1592	1592	0	1592
1988	202	1260	1462	1418	44	1462
1989	200	983	1183	1183	0	1183
1990	215	1433	1648	1648	0	1648
1991	197	1394	1591	1571	20	1591
1992	284	1887	2171	2171	0	2171
1993	257	1954	2211	2159	52	2211
1994	127	1268	1395	1226	169	1395
1995	0	1582	1582	1474	108	1582
1996	67	1735	1802	1440	362	1802
1997	0	2425	2425	1777	648	2425
1998	112	2059	2171	1281	890	2171
1999	37	2023	2060	1692	368	2060
2000	0	2023	2023	1380	643	2023
2001	41	2394	2435	1410	1025	2435
2002	0	2521	2521	1987	534	2521
2003	0	2146	2146	1206	940	2146
2004	0	1920	1920	1180	740	1920
2005	0	2417	2417	1384	1033	2417
2006	12	2427	2439	1246	1193	2439
2007	11	1829	1840	1085	755	1840
2008	0	1973	1973	1135	838	1973
2009	0	1950	1950	906	1044	1950
2010	0	2115	2115	815	1300	2115
2011	0	1634	1634	861	773	1634
2012	0	1529	1529	660	869	1529
2013	0	1979	1979	518	1461	1979
2014	14	2085	2099	861	1238	2099
2015	25	1547	1572	670	902	1572
2016	0	1332	1332	610	722	1332
2017	0	947	947	511	436	947

Table B1- 6 New Brunswick, Canada, Atlantic herring weir catches (numbers)

	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Age11+
1965	992000	852368000	65449000	53194000	6897000	240000	116000	77000	0	0	0
1966	3899000	151087000	432061000	49134000	30162000	1182000	28000	13000	22000	29000	0
1967	127374000	194566000	57421000	111164000	12573000	4326000	1170000	119000	3000	0	0
1968	2409000	758766000	51933000	25098000	31655000	3957000	3141000	757000	77000	10000	0
1969	71191000	375586000	101361000	5067000	9845000	7692000	6449000	2025000	300000	3000	0
1970	3553000	348916000	9924000	12598000	6034000	3788000	2356000	893000	61000	10000	0
1971	92253000	183690000	37348000	7925000	3912000	2078000	3068000	1195000	332000	52000	62000
1972	8102000	660547000	6446000	10817000	4226000	2005000	1029000	1161000	354000	34000	11000
1973	31803000	149051000	125965000	14773000	1038000	529000	57000	121000	56000	4000	22000
1974	3259000	246044000	43483000	31147000	1227000	48000	54000	35000	38000	27000	37000
1975	16880000	462977000	57228000	9555000	16380000	2183000	1111000	916000	294000	158000	174000
1976	51791000	199268000	104624000	19989000	14911000	10128000	1601000	366000	457000	193000	112000
1977	459109000	122921000	10305000	20941000	7237000	7050000	4674000	230000	5000	0	1000
1978	213778000	894372000	52125000	3665000	810000	1064000	280000	132000	0	0	0
1979	2396000	423731000	247356000	12236000	822000	841000	479000	1005000	190000	0	0
1980	257995000	5325000	62087000	21615000	924000	125000	124000	67000	57000	63000	0
1981	53336000	294720000	18781000	10199000	5368000	306000	46000	34000	27000	0	0
1982	30210000	395416000	73197000	3199000	1795000	1596000	196000	42000	68000	0	0
1983	2532000	135283000	21684000	7526000	444000	398000	189000	0	0	0	0
1984	14353000	82920000	17292000	5658000	4332000	611000	251000	15000	85000	0	0
1985	20295000	385381000	45879000	17936000	7411000	3507000	304000	71000	73000	0	0
1986	3210000	136292000	119736000	24061000	10636000	4644000	2272000	335000	94000	66000	9000
1987	35677000	129348000	47981000	53150000	22941000	7097000	2472000	606000	173000	96000	0
1988	76053000	347765000	45078000	22366000	38843000	14212000	1680000	101000	247000	1000	9000
1989	26855000	331014000	81410000	21442000	22723000	43020000	11532000	3095000	810000	121000	249000
1990	12576000	454802000	69004000	30689000	6358000	7230000	15031000	3420000	2520000	620000	310000
1991	5530000	338263000	44450000	23618000	9532000	3154000	2620000	3436000	1461000	267000	150000
1992	799000	375772000	97678000	36438000	10378000	3992000	1613000	1360000	558000	245000	44000
1993	1718000	244079000	106099000	37186000	23218000	12260000	4915000	1120000	1101000	864000	175000
1994	1986000	291956000	63902000	9972000	16258000	9332000	3893000	1479000	1080000	544000	334000
1995	57844000	259741000	40122000	14803000	1822000	1567000	1549000	30000	0	0	0
1996	5351000	269431000	22390000	9342000	4302000	1147000	1273000	426000	38000	9000	2000
1997	9309000	216159000	113197000	11333000	3597000	523000	206000	95000	11000	0	0
1998	440000	387723000	36062000	9595000	3404000	1842000	297000	69000	25000	1000	0
1999	167679	106127770	100722414	11903080	9057476	3968746	1365910	154714	3950	3909	8434
2000	1665260	256784705	8082353	7871514	5376908	1416883	521421	101422	190	0	0
2001	1320542	113200008	119194370	8018810	5712883	1823813	588419	95017	101838	2081	0
2002	31858563	180051484	16260128	11528872	3020062	432017	101972	48714	18817	19556	11509
2003	11470685	162210672	15488021	2912807	1987414	456774	128273	27994	27934	13587	12487
2004	6711148	184123131	103911073	18753448	2537258	1751082	305572	358008	92686	31016	45060
2005	1152478	102401310	73912834	19379433	4269372	533907	268965	109207	13692	450	2466
2006	201206756	139578332	25001134	3786465	3705592	1275745	684331	138912	6539	842	1725
2007	6322626	571186007	31093039	2644604	812012	1274805	419924	63163	13985	1667	220
2008	27894408	122185141	19783355	203318	82469	105017	120277	45529	17154	1270	76
2009	12987445	99615384	3302958	141258	3842	1285	832	237	79	0	0
2010	7224	371400620	16967663	522825	463391	29356	21701	28636	16157	5620	612
2011	14254158	44743409	21030320	2153126	262891	61326	3942	0	0	0	0
2012	23399306	4309339	467710	611200	232280	62349	16952	3094	1028	543	287
2013	35483478	126916853	10474516	642836	435504	216325	52156	13511	993	0	253
2014	21037481	38784963	1422384	711520	288369	218518	75676	30661	8797	355	1892
2015	429076	5944638	49852	6985	3867	1622	748	0	748	0	0
2016	832028	61493618	9108761	1707005	657193	253407	145416	180769	15169	5202	0
2017	2427711	13588301	2360908	5096051	1860612	1233993	583536	284588	82045	22132	0

Table B1- 7 Mobile fleet age composition proportions at age

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8+**
1965	0.001	0.965	0.026	0.008	0.000	0.000	0.000	0.000
1966	0.000	0.416	0.529	0.017	0.027	0.009	0.002	0.000
1967	0.000	0.048	0.213	0.168	0.094	0.138	0.265	0.075
1968	0.011	0.716	0.210	0.039	0.024	0.000	0.000	0.000
1969	0.096	0.257	0.486	0.062	0.013	0.009	0.019	0.058
1970	0.075	0.250	0.111	0.201	0.143	0.074	0.063	0.082
1971	0.053	0.028	0.209	0.182	0.184	0.125	0.084	0.135
1972	0.017	0.234	0.087	0.141	0.182	0.164	0.098	0.077
1973	0.017	0.153	0.524	0.139	0.052	0.038	0.043	0.034
1974	0.008	0.103	0.126	0.629	0.070	0.023	0.021	0.020
1975	0.007	0.025	0.066	0.140	0.635	0.061	0.029	0.037
1976	0.000	0.007	0.176	0.089	0.114	0.545	0.040	0.030
1977	0.013	0.174	0.078	0.264	0.068	0.076	0.293	0.033
1978	0.008	0.201	0.263	0.119	0.191	0.026	0.037	0.155
1979	0.000	0.209	0.332	0.225	0.075	0.092	0.014	0.053
1980	0.001	0.106	0.425	0.363	0.053	0.015	0.022	0.014
1981	0.000	0.107	0.039	0.495	0.299	0.033	0.010	0.017
1982	0.002	0.233	0.200	0.040	0.297	0.186	0.020	0.023
1983	0.033	0.369	0.243	0.191	0.011	0.079	0.062	0.013
1984	0.000	0.222	0.464	0.160	0.107	0.007	0.026	0.013
1985	0.001	0.178	0.157	0.401	0.154	0.086	0.004	0.019
1986	0.005	0.291	0.431	0.105	0.101	0.043	0.019	0.005
1987	0.001	0.155	0.306	0.428	0.057	0.038	0.010	0.005
1988	0.001	0.124	0.230	0.210	0.321	0.077	0.026	0.011
1989	0.000	0.322	0.259	0.106	0.093	0.160	0.041	0.019
1990	0.000	0.172	0.333	0.135	0.066	0.073	0.131	0.089
1991	0.000	0.145	0.281	0.182	0.146	0.074	0.062	0.110
1992	0.000	0.093	0.278	0.166	0.182	0.120	0.066	0.096
1993	0.000	0.128	0.245	0.193	0.181	0.108	0.081	0.064
1994	0.000	0.152	0.236	0.134	0.169	0.159	0.087	0.064
1995	0.003	0.198	0.128	0.069	0.073	0.164	0.198	0.168
1996	0.001	0.267	0.159	0.081	0.103	0.202	0.134	0.052
1997	0.000	0.080	0.551	0.094	0.067	0.084	0.093	0.031
1998	0.000	0.162	0.178	0.425	0.100	0.048	0.050	0.037
1999	0.001	0.148	0.346	0.117	0.228	0.093	0.040	0.028
2000	0.000	0.272	0.070	0.153	0.189	0.231	0.058	0.027
2001	0.000	0.078	0.422	0.065	0.111	0.142	0.141	0.040
2002	0.009	0.091	0.169	0.341	0.131	0.099	0.101	0.059
2003	0.002	0.287	0.193	0.083	0.228	0.079	0.075	0.054
2004	0.001	0.199	0.463	0.112	0.080	0.093	0.041	0.011
2005	0.000	0.064	0.443	0.276	0.080	0.074	0.052	0.011
2006	0.000	0.076	0.292	0.384	0.149	0.044	0.031	0.024
2007	0.000	0.241	0.216	0.201	0.196	0.101	0.029	0.017
2008	0.000	0.020	0.434	0.140	0.121	0.153	0.082	0.049
2009	0.000	0.107	0.135	0.413	0.101	0.096	0.104	0.045
2010	0.000	0.420	0.218	0.089	0.177	0.043	0.034	0.019
2011	0.000	0.049	0.803	0.104	0.022	0.017	0.003	0.003
2012	0.002	0.127	0.049	0.652	0.111	0.024	0.027	0.010
2013	0.000	0.156	0.154	0.085	0.499	0.089	0.012	0.005
2014	0.000	0.073	0.515	0.100	0.049	0.221	0.038	0.004
2015	0.000	0.133	0.100	0.488	0.065	0.063	0.134	0.018
2016	0.000	0.015	0.194	0.158	0.368	0.096	0.062	0.107
2017	0.000	0.014	0.184	0.328	0.118	0.267	0.033	0.057

Table B1- 8 Fixed fleet age composition proportions at age

	1	2	3	4	5	6	7	8+
1965	0.027	0.865	0.066	0.025	0.004	0.000	0.004	0.009
1966	0.032	0.368	0.523	0.042	0.025	0.001	0.003	0.006
1967	0.159	0.487	0.162	0.153	0.022	0.008	0.002	0.008
1968	0.069	0.801	0.085	0.017	0.022	0.002	0.002	0.001
1969	0.120	0.619	0.219	0.009	0.013	0.010	0.008	0.003
1970	0.057	0.848	0.036	0.030	0.013	0.008	0.005	0.002
1971	0.320	0.473	0.123	0.029	0.017	0.014	0.012	0.012
1972	0.008	0.930	0.012	0.013	0.015	0.010	0.008	0.004
1973	0.100	0.460	0.387	0.044	0.005	0.002	0.001	0.001
1974	0.056	0.741	0.126	0.073	0.004	0.000	0.000	0.000
1975	0.055	0.791	0.104	0.017	0.027	0.003	0.001	0.002
1976	0.083	0.635	0.227	0.023	0.017	0.013	0.002	0.001
1977	0.436	0.452	0.060	0.028	0.008	0.008	0.008	0.000
1978	0.154	0.780	0.059	0.003	0.002	0.001	0.000	0.001
1979	0.004	0.764	0.219	0.010	0.001	0.001	0.001	0.001
1980	0.349	0.293	0.290	0.064	0.003	0.000	0.000	0.001
1981	0.042	0.903	0.026	0.016	0.012	0.001	0.000	0.000
1982	0.071	0.809	0.111	0.004	0.003	0.002	0.000	0.000
1983	0.126	0.769	0.077	0.025	0.001	0.001	0.001	0.000
1984	0.152	0.654	0.119	0.039	0.030	0.004	0.002	0.001
1985	0.060	0.823	0.072	0.027	0.011	0.005	0.000	0.000
1986	0.074	0.438	0.364	0.072	0.030	0.013	0.006	0.001
1987	0.187	0.454	0.131	0.140	0.060	0.019	0.007	0.002
1988	0.119	0.688	0.071	0.035	0.061	0.022	0.003	0.001
1989	0.044	0.645	0.141	0.036	0.037	0.071	0.019	0.007
1990	0.020	0.762	0.113	0.049	0.010	0.012	0.024	0.011
1991	0.011	0.806	0.094	0.047	0.019	0.006	0.005	0.011
1992	0.001	0.749	0.164	0.057	0.016	0.006	0.003	0.003
1993	0.003	0.616	0.221	0.073	0.046	0.024	0.010	0.007
1994	0.005	0.741	0.153	0.024	0.039	0.022	0.009	0.008
1995	0.153	0.688	0.106	0.039	0.005	0.004	0.004	0.000
1996	0.018	0.859	0.070	0.029	0.013	0.004	0.004	0.002
1997	0.026	0.610	0.319	0.032	0.010	0.001	0.001	0.000
1998	0.001	0.843	0.082	0.048	0.012	0.007	0.005	0.002
1999	0.001	0.464	0.418	0.052	0.038	0.018	0.006	0.004
2000	0.006	0.911	0.029	0.028	0.019	0.005	0.002	0.000
2001	0.005	0.453	0.477	0.032	0.023	0.007	0.002	0.001
2002	0.131	0.740	0.067	0.047	0.012	0.002	0.000	0.000
2003	0.059	0.833	0.080	0.015	0.010	0.002	0.001	0.000
2004	0.021	0.578	0.326	0.059	0.008	0.005	0.001	0.002
2005	0.006	0.507	0.366	0.096	0.021	0.003	0.001	0.001
2006	0.521	0.363	0.086	0.015	0.010	0.003	0.002	0.000
2007	0.010	0.925	0.056	0.005	0.001	0.002	0.001	0.000
2008	0.164	0.717	0.116	0.001	0.000	0.001	0.001	0.000
2009	0.112	0.858	0.028	0.001	0.000	0.000	0.000	0.000
2010	0.000	0.954	0.044	0.001	0.001	0.000	0.000	0.000
2011	0.173	0.542	0.255	0.026	0.003	0.001	0.000	0.000
2012	0.804	0.148	0.016	0.021	0.008	0.002	0.001	0.000
2013	0.204	0.728	0.060	0.004	0.002	0.001	0.000	0.000
2014	0.297	0.627	0.055	0.011	0.004	0.004	0.001	0.001
2015	0.037	0.514	0.007	0.184	0.038	0.063	0.141	0.015
2016	0.011	0.827	0.122	0.023	0.009	0.003	0.002	0.003
2017	0.088	0.493	0.086	0.185	0.068	0.045	0.021	0.014

Table B1- 9 Catch weights at age (kg)

	1	2	3	4	5	6	7	8+
1965	0.009	0.024	0.055	0.112	0.134	0.272	0.189	0.189
1966	0.011	0.027	0.068	0.142	0.219	0.272	0.189	0.189
1967	0.009	0.028	0.062	0.114	0.170	0.210	0.238	0.351
1968	0.058	0.034	0.068	0.143	0.186	0.239	0.276	0.276
1969	0.010	0.035	0.100	0.137	0.210	0.240	0.288	0.288
1970	0.010	0.044	0.121	0.159	0.186	0.232	0.269	0.413
1971	0.012	0.044	0.129	0.168	0.199	0.242	0.289	0.346
1972	0.026	0.039	0.113	0.175	0.212	0.260	0.292	0.361
1973	0.010	0.044	0.110	0.137	0.219	0.280	0.331	0.370
1974	0.010	0.038	0.103	0.167	0.203	0.271	0.293	0.293
1975	0.016	0.044	0.107	0.177	0.206	0.244	0.288	0.375
1976	0.014	0.036	0.106	0.174	0.205	0.229	0.263	0.333
1977	0.012	0.037	0.094	0.153	0.196	0.227	0.236	0.305
1978	0.011	0.037	0.096	0.158	0.196	0.220	0.239	0.318
1979	0.006	0.031	0.082	0.169	0.216	0.243	0.265	0.294
1980	0.012	0.041	0.097	0.150	0.229	0.265	0.291	0.332
1981	0.010	0.041	0.098	0.177	0.213	0.281	0.310	0.356
1982	0.019	0.042	0.104	0.204	0.229	0.253	0.305	0.367
1983	0.018	0.041	0.124	0.199	0.219	0.283	0.319	0.410
1984	0.014	0.041	0.117	0.154	0.195	0.209	0.291	0.305
1985	0.017	0.036	0.096	0.148	0.162	0.188	0.198	0.220
1986	0.018	0.042	0.101	0.159	0.210	0.236	0.247	0.266
1987	0.011	0.041	0.092	0.137	0.088	0.147	0.145	0.160
1988	0.007	0.031	0.091	0.106	0.123	0.132	0.190	0.208
1989	0.009	0.031	0.066	0.104	0.116	0.133	0.157	0.157
1990	0.004	0.029	0.080	0.138	0.172	0.169	0.179	0.235
1991	0.004	0.036	0.074	0.124	0.150	0.184	0.200	0.244
1992	0.009	0.035	0.073	0.124	0.139	0.164	0.191	0.249
1993	0.003	0.032	0.078	0.119	0.125	0.148	0.183	0.265
1994	0.008	0.029	0.070	0.118	0.134	0.152	0.162	0.166
1995	0.014	0.046	0.090	0.118	0.134	0.149	0.160	0.259
1996	0.024	0.043	0.083	0.120	0.146	0.164	0.179	0.280
1997	0.017	0.045	0.085	0.118	0.146	0.167	0.182	0.182
1998	0.021	0.037	0.080	0.112	0.133	0.158	0.178	0.222
1999	0.026	0.048	0.087	0.116	0.132	0.149	0.176	0.216
2000	0.018	0.060	0.101	0.127	0.147	0.159	0.182	0.244
2001	0.005	0.047	0.089	0.127	0.147	0.161	0.175	0.240
2002	0.020	0.045	0.093	0.121	0.138	0.158	0.169	0.200
2003	0.015	0.052	0.090	0.130	0.149	0.166	0.184	0.207
2004	0.011	0.043	0.092	0.125	0.152	0.166	0.186	0.209
2005	0.019	0.042	0.083	0.123	0.149	0.170	0.188	0.252
2006	0.019	0.066	0.085	0.120	0.147	0.172	0.188	0.198
2007	0.016	0.047	0.085	0.118	0.141	0.161	0.185	0.199
2008	0.016	0.041	0.100	0.131	0.152	0.169	0.180	0.221
2009	0.004	0.047	0.090	0.133	0.156	0.172	0.184	0.206
2010	0.028	0.036	0.072	0.113	0.142	0.162	0.174	0.174
2011	0.019	0.044	0.069	0.100	0.138	0.160	0.189	0.183
2012	0.013	0.049	0.085	0.096	0.109	0.145	0.160	0.184
2013	0.012	0.050	0.070	0.107	0.118	0.129	0.155	0.204
2014	0.012	0.060	0.096	0.106	0.144	0.146	0.150	0.165
2015	0.025	0.043	0.087	0.126	0.136	0.158	0.158	0.206
2016	0.025	0.047	0.068	0.107	0.143	0.151	0.166	0.183
2017	0.014	0.044	0.085	0.114	0.140	0.158	0.167	0.167

Table B1- 10 Spawning stock biomass weights at age (kg)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8+**
1965	0.013	0.038	0.095	0.113	0.202	0.265	0.298	0.355
1966	0.016	0.047	0.096	0.170	0.224	0.279	0.302	0.355
1967	0.016	0.043	0.107	0.172	0.206	0.227	0.242	0.371
1968	0.011	0.038	0.069	0.178	0.223	0.265	0.298	0.355
1969	0.011	0.041	0.102	0.134	0.222	0.265	0.298	0.311
1970	0.011	0.061	0.126	0.163	0.191	0.239	0.276	0.419
1971	0.014	0.068	0.144	0.170	0.202	0.248	0.296	0.353
1972	0.031	0.069	0.154	0.197	0.235	0.268	0.289	0.344
1973	0.011	0.051	0.133	0.170	0.238	0.295	0.352	0.379
1974	0.008	0.045	0.124	0.169	0.196	0.270	0.290	0.352
1975	0.015	0.055	0.133	0.188	0.211	0.248	0.295	0.362
1976	0.015	0.088	0.132	0.184	0.210	0.236	0.278	0.371
1977	0.013	0.045	0.131	0.175	0.215	0.243	0.249	0.342
1978	0.032	0.051	0.119	0.178	0.208	0.239	0.252	0.321
1979	0.015	0.073	0.133	0.187	0.229	0.253	0.302	0.389
1980	0.007	0.054	0.104	0.185	0.250	0.294	0.319	0.366
1981	0.015	0.039	0.135	0.192	0.236	0.301	0.339	0.379
1982	0.017	0.050	0.139	0.200	0.240	0.272	0.328	0.368
1983	0.024	0.069	0.144	0.214	0.265	0.297	0.332	0.413
1984	0.007	0.064	0.140	0.193	0.239	0.286	0.313	0.379
1985	0.006	0.047	0.146	0.208	0.237	0.268	0.318	0.269
1986	0.032	0.057	0.116	0.176	0.227	0.252	0.271	0.319
1987	0.010	0.068	0.108	0.159	0.202	0.238	0.256	0.315
1988	0.027	0.066	0.117	0.154	0.192	0.229	0.264	0.316
1989	0.027	0.068	0.116	0.172	0.201	0.234	0.260	0.329
1990	0.024	0.062	0.106	0.156	0.189	0.216	0.233	0.312
1991	0.024	0.063	0.096	0.142	0.171	0.205	0.225	0.306
1992	0.024	0.060	0.102	0.135	0.164	0.190	0.220	0.305
1993	0.024	0.047	0.096	0.137	0.156	0.180	0.209	0.309
1994	0.024	0.054	0.086	0.120	0.138	0.159	0.180	0.307
1995	0.027	0.051	0.095	0.123	0.145	0.162	0.175	0.275
1996	0.028	0.055	0.088	0.125	0.150	0.171	0.188	0.228
1997	0.014	0.059	0.091	0.124	0.150	0.174	0.194	0.222
1998	0.027	0.052	0.092	0.117	0.138	0.164	0.187	0.216
1999	0.026	0.060	0.091	0.123	0.140	0.157	0.186	0.205
2000	0.027	0.065	0.111	0.137	0.156	0.172	0.198	0.221
2001	0.033	0.056	0.099	0.134	0.153	0.166	0.181	0.201
2002	0.030	0.059	0.099	0.126	0.143	0.167	0.183	0.195
2003	0.027	0.059	0.099	0.137	0.153	0.171	0.192	0.198
2004	0.027	0.047	0.091	0.129	0.155	0.173	0.194	0.203
2005	0.027	0.054	0.087	0.131	0.159	0.183	0.199	0.198
2006	0.027	0.062	0.089	0.133	0.163	0.184	0.203	0.204
2007	0.027	0.064	0.106	0.140	0.164	0.184	0.203	0.207
2008	0.027	0.068	0.106	0.135	0.162	0.175	0.188	0.201
2009	0.027	0.057	0.095	0.138	0.159	0.179	0.191	0.209
2010	0.027	0.043	0.089	0.121	0.146	0.169	0.183	0.203
2011	0.027	0.049	0.076	0.110	0.141	0.168	0.183	0.198
2012	0.032	0.049	0.090	0.107	0.123	0.155	0.188	0.198
2013	0.027	0.061	0.090	0.124	0.132	0.144	0.180	0.199
2014	0.027	0.066	0.106	0.119	0.155	0.158	0.165	0.196
2015	0.027	0.057	0.103	0.136	0.148	0.169	0.170	0.195
2016	0.027	0.065	0.080	0.114	0.151	0.158	0.171	0.190
2017	0.027	0.058	0.093	0.121	0.148	0.169	0.186	0.185

Table B1- 11 Jan. 1 Weights at age (kg)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8+**
1965	0.007	0.024	0.071	0.080	0.172	0.248	0.287	0.356
1966	0.010	0.025	0.060	0.127	0.159	0.237	0.283	0.352
1967	0.010	0.026	0.071	0.129	0.187	0.226	0.260	0.360
1968	0.006	0.025	0.055	0.138	0.196	0.234	0.260	0.354
1969	0.005	0.021	0.062	0.096	0.199	0.243	0.281	0.326
1970	0.004	0.026	0.072	0.129	0.160	0.230	0.270	0.364
1971	0.006	0.027	0.094	0.146	0.182	0.218	0.266	0.360
1972	0.024	0.031	0.102	0.168	0.200	0.233	0.268	0.345
1973	0.005	0.040	0.096	0.162	0.217	0.263	0.307	0.356
1974	0.003	0.022	0.080	0.150	0.183	0.254	0.293	0.366
1975	0.006	0.021	0.077	0.153	0.189	0.221	0.282	0.353
1976	0.009	0.036	0.085	0.156	0.199	0.223	0.263	0.363
1977	0.007	0.026	0.107	0.152	0.199	0.226	0.242	0.351
1978	0.021	0.026	0.073	0.153	0.191	0.227	0.248	0.324
1979	0.008	0.048	0.082	0.149	0.202	0.229	0.269	0.341
1980	0.003	0.029	0.087	0.157	0.216	0.260	0.284	0.365
1981	0.008	0.017	0.085	0.141	0.209	0.274	0.316	0.370
1982	0.008	0.027	0.074	0.164	0.215	0.253	0.314	0.373
1983	0.015	0.034	0.085	0.173	0.230	0.267	0.301	0.389
1984	0.003	0.039	0.098	0.167	0.226	0.275	0.305	0.395
1985	0.002	0.018	0.097	0.171	0.214	0.253	0.302	0.268
1986	0.022	0.019	0.074	0.160	0.217	0.244	0.270	0.252
1987	0.004	0.047	0.079	0.136	0.189	0.232	0.254	0.312
1988	0.017	0.026	0.089	0.129	0.175	0.215	0.251	0.309
1989	0.018	0.043	0.088	0.142	0.176	0.212	0.244	0.317
1990	0.015	0.041	0.085	0.135	0.180	0.208	0.234	0.314
1991	0.015	0.039	0.077	0.123	0.163	0.197	0.221	0.301
1992	0.017	0.038	0.080	0.114	0.153	0.180	0.212	0.298
1993	0.016	0.034	0.076	0.118	0.145	0.172	0.199	0.298
1994	0.017	0.036	0.064	0.107	0.138	0.158	0.180	0.298
1995	0.019	0.035	0.072	0.103	0.132	0.150	0.167	0.280
1996	0.019	0.039	0.067	0.109	0.136	0.158	0.175	0.237
1997	0.007	0.041	0.071	0.105	0.137	0.162	0.182	0.193
1998	0.018	0.027	0.074	0.103	0.131	0.157	0.180	0.148
1999	0.016	0.040	0.069	0.106	0.128	0.147	0.175	0.211
2000	0.019	0.041	0.082	0.112	0.139	0.155	0.176	0.211
2001	0.025	0.039	0.080	0.122	0.145	0.161	0.176	0.210
2002	0.021	0.044	0.075	0.112	0.138	0.160	0.174	0.198
2003	0.021	0.042	0.076	0.117	0.139	0.156	0.179	0.197
2004	0.019	0.036	0.073	0.113	0.146	0.163	0.182	0.201
2005	0.018	0.038	0.064	0.109	0.143	0.168	0.186	0.202
2006	0.018	0.041	0.069	0.108	0.146	0.171	0.193	0.203
2007	0.017	0.042	0.081	0.112	0.148	0.173	0.193	0.207
2008	0.019	0.043	0.082	0.120	0.151	0.169	0.186	0.205
2009	0.021	0.039	0.080	0.121	0.147	0.170	0.183	0.205
2010	0.020	0.034	0.071	0.107	0.142	0.164	0.181	0.202
2011	0.020	0.036	0.057	0.099	0.131	0.157	0.176	0.202
2012	0.023	0.036	0.066	0.090	0.116	0.148	0.178	0.198
2013	0.017	0.044	0.066	0.106	0.119	0.133	0.167	0.199
2014	0.019	0.042	0.080	0.104	0.139	0.144	0.154	0.198
2015	0.017	0.039	0.082	0.120	0.133	0.162	0.164	0.195
2016	0.018	0.042	0.068	0.108	0.143	0.153	0.170	0.192
2017	0.018	0.040	0.078	0.098	0.130	0.160	0.171	0.187

Table B1- 12 Proportion mature at age

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8+**
1965	0.0000	0.0529	0.2143	0.8000	1.0000	1.0000	1.0000	1.0000
1966	0.0000	0.0264	0.3082	0.8304	0.9979	0.9993	1.0000	1.0000
1967	0.0000	0.0264	0.3082	0.8304	0.9979	0.9993	1.0000	1.0000
1968	0.0000	0.0264	0.3082	0.8304	0.9979	0.9993	1.0000	1.0000
1969	0.0000	0.0264	0.3082	0.8304	0.9979	0.9993	1.0000	1.0000
1970	0.0000	0.0264	0.3082	0.8304	0.9979	0.9993	1.0000	1.0000
1971	0.0000	0.0000	0.4021	0.8608	0.9959	0.9986	1.0000	1.0000
1972	0.0000	0.0264	0.6241	0.9304	0.9979	0.9993	1.0000	1.0000
1973	0.0000	0.0529	0.8462	1.0000	1.0000	1.0000	1.0000	1.0000
1974	0.0000	0.0264	0.5514	0.9828	1.0000	1.0000	1.0000	1.0000
1975	0.0000	0.0264	0.5514	0.9828	1.0000	1.0000	1.0000	1.0000
1976	0.0000	0.0264	0.5514	0.9828	1.0000	1.0000	1.0000	1.0000
1977	0.0000	0.0000	0.2566	0.9655	1.0000	1.0000	1.0000	1.0000
1978	0.0000	0.0000	0.2722	0.9782	1.0000	0.9762	1.0000	1.0000
1979	0.0000	0.0000	0.4303	0.9944	1.0000	1.0000	1.0000	1.0000
1980	0.0000	0.0529	0.1641	0.9680	1.0000	1.0000	1.0000	1.0000
1981	0.0000	0.0000	0.1485	0.9711	0.9972	1.0000	1.0000	1.0000
1982	0.0000	0.0000	0.6276	1.0000	1.0000	1.0000	1.0000	1.0000
1983	0.0000	0.0000	0.5831	0.9938	1.0000	1.0000	1.0000	1.0000
1984	0.0000	0.0000	0.6102	1.0000	1.0000	1.0000	1.0000	1.0000
1985	0.0000	0.0833	0.7166	0.9947	1.0000	1.0000	1.0000	1.0000
1986	0.0000	0.0000	0.5039	0.9744	1.0000	1.0000	1.0000	1.0000
1987	0.0000	0.2000	0.2986	0.9517	1.0000	1.0000	1.0000	1.0000
1988	0.0000	0.0000	0.2966	0.9769	1.0000	1.0000	1.0000	1.0000
1989	0.0000	0.0000	0.4046	0.9837	1.0000	1.0000	0.9762	1.0000
1990	0.0000	0.0000	0.2378	0.9646	1.0000	1.0000	1.0000	1.0000
1991	0.0000	0.0000	0.2297	0.9701	1.0000	1.0000	1.0000	1.0000
1992	0.0000	0.0529	0.3982	0.9632	1.0000	1.0000	1.0000	1.0000
1993	0.0000	0.0529	0.3186	0.9845	0.9954	1.0000	1.0000	1.0000
1994	0.0000	0.0529	0.1646	0.9082	1.0000	1.0000	1.0000	1.0000
1995	0.0000	0.0529	0.3370	0.8939	1.0000	1.0000	1.0000	1.0000
1996	0.0000	0.0529	0.4500	0.9467	1.0000	1.0000	1.0000	1.0000
1997	0.0000	0.6667	0.8523	1.0000	1.0000	1.0000	1.0000	0.9756
1998	0.0000	0.0529	0.6117	0.9891	1.0000	0.9804	1.0000	1.0000
1999	0.0000	0.0000	0.3548	0.9184	0.9926	1.0000	0.9677	1.0000
2000	0.0000	0.0000	0.6535	0.9919	1.0000	1.0000	1.0000	0.9412
2001	0.0000	0.0000	0.8438	1.0000	1.0000	0.9919	0.9913	1.0000
2002	0.0000	0.0000	0.5252	0.9802	1.0000	1.0000	1.0000	1.0000
2003	0.0000	0.0400	0.5924	0.9552	1.0000	1.0000	1.0000	0.9500
2004	0.0000	0.3333	0.6257	1.0000	1.0000	1.0000	1.0000	1.0000
2005	0.0000	0.5000	0.5662	1.0000	1.0000	1.0000	1.0000	1.0000
2006	0.0000	0.0000	0.3370	0.9927	1.0000	1.0000	1.0000	1.0000
2007	0.0000	0.0063	0.7798	0.9921	1.0000	1.0000	1.0000	1.0000
2008	0.0000	0.0000	0.7890	0.9899	1.0000	1.0000	1.0000	1.0000
2009	0.0000	0.0000	0.7317	1.0000	1.0000	1.0000	1.0000	1.0000
2010	0.0000	0.0087	0.7324	0.9917	1.0000	0.9800	1.0000	1.0000
2011	0.0000	0.0000	0.4842	0.9830	1.0000	1.0000	1.0000	1.0000
2012	0.0000	0.0000	0.6230	0.9906	1.0000	1.0000	1.0000	1.0000
2013	0.0000	0.0660	0.5556	0.9242	0.9973	1.0000	1.0000	1.0000
2014	0.0000	0.0000	0.8817	1.0000	1.0000	1.0000	1.0000	1.0000
2015	0.0000	0.0000	0.6543	0.9965	1.0000	1.0000	1.0000	1.0000
2016	0.0000	0.0000	0.5306	0.7778	1.0000	1.0000	1.0000	1.0000
2017	0.0000	0.0000	0.7765	0.9110	1.0000	1.0000	1.0000	1.0000

Table B1- 13 Number of samples used for maturity at age each year

Year	Maturity Samples
1965	21
1966	0
1967	0
1968	0
1969	0
1970	0
1971	3692
1972	0
1973	84
1974	0
1975	0
1976	0
1977	366
1978	1504
1979	1307
1980	1604
1981	1072
1982	751
1983	993
1984	1107
1985	1037
1986	440
1987	710
1988	468
1989	581
1990	486
1991	674
1992	842
1993	1033
1994	502
1995	804
1996	567
1997	1166
1998	583
1999	640
2000	672
2001	902
2002	998
2003	594
2004	289
2005	959
2006	985
2007	716
2008	744
2009	804
2010	923
2011	1093
2012	851
2013	775
2014	915
2015	602
2016	352
2017	449

Figure B1- 1 Length (cm) composition of Atlantic herring caught by purse seine, midwater trawl, or paired midwater trawl during 2007-2016

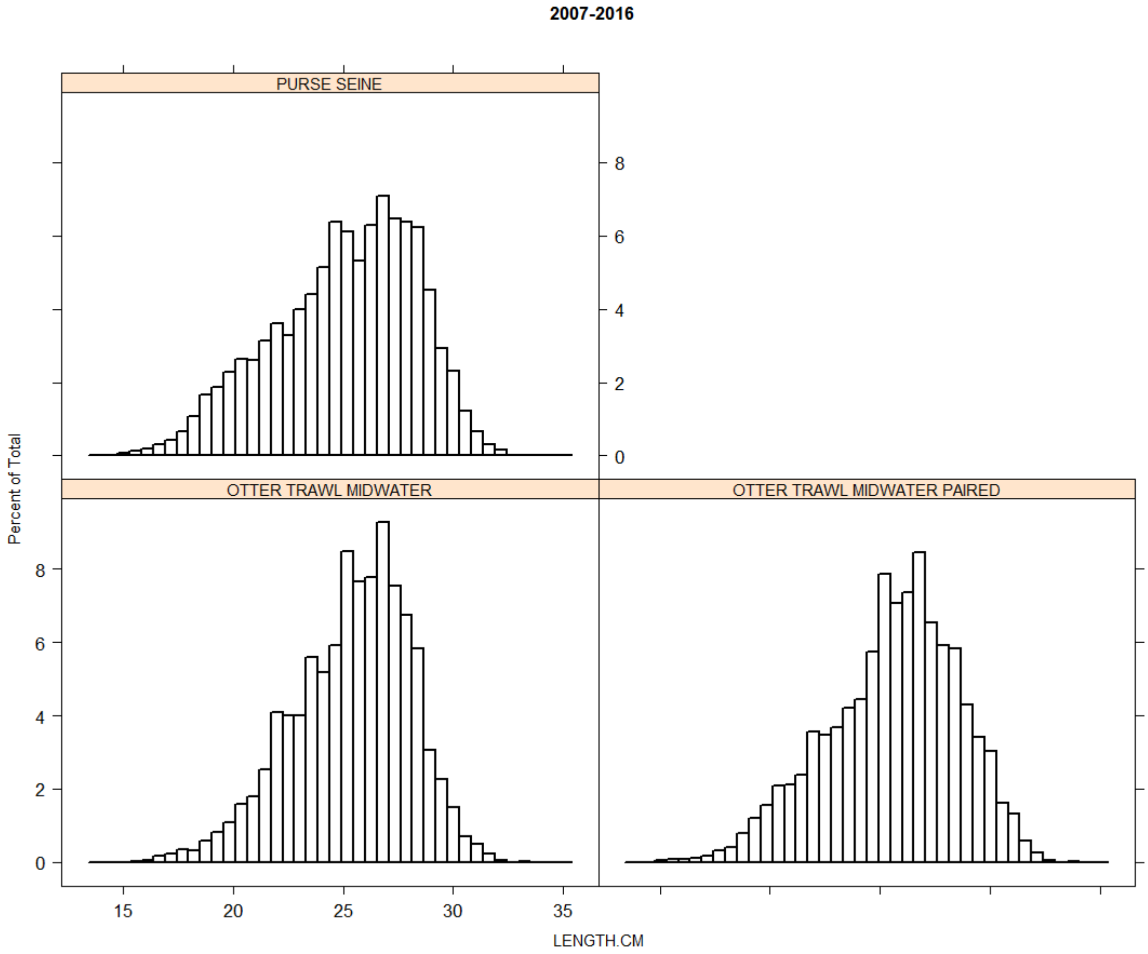


Figure B1- 2 Example of a Atlantic herring bimodal length frequency (cm) observed for the purse seine gear but not midwater trawls (data from 2012)

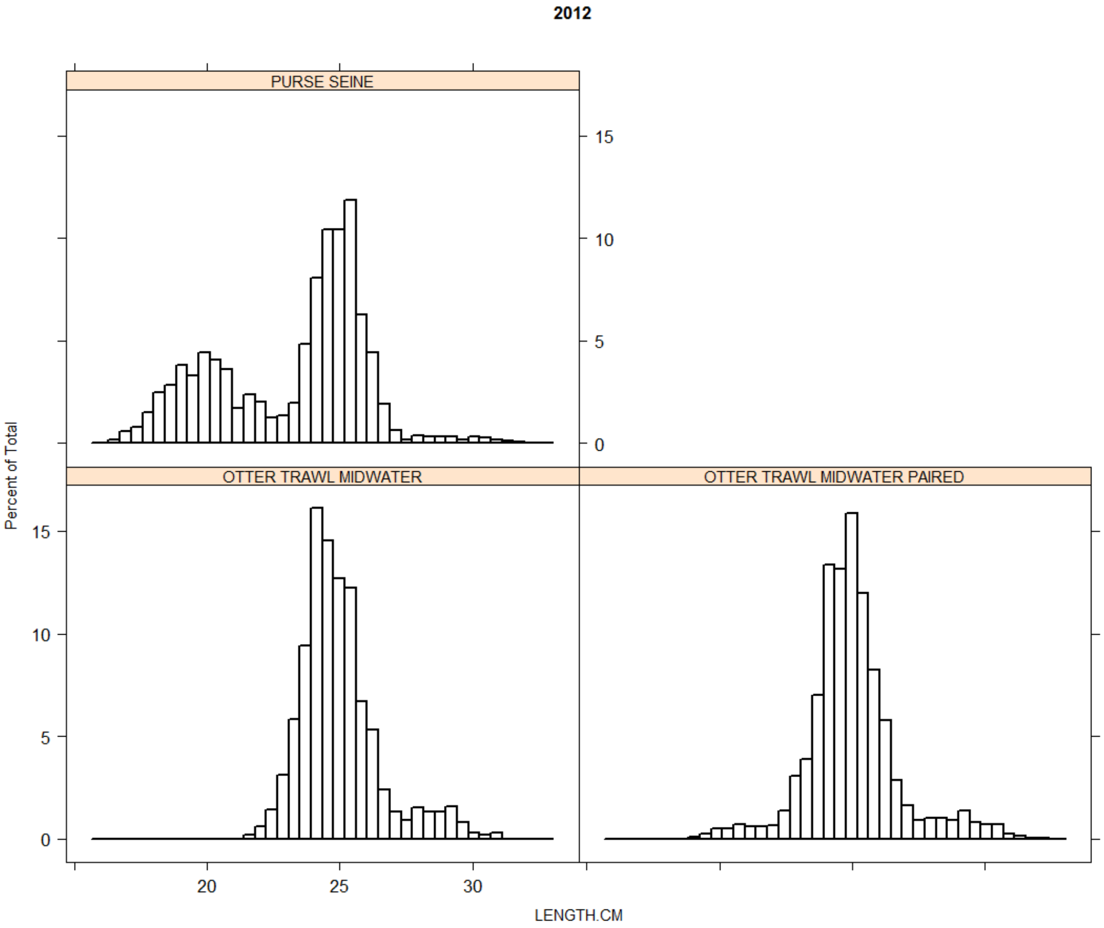


Figure B1- 3 Atlantic herring catch (mt) by purse seine, midwater trawl, and paired midwater trawl

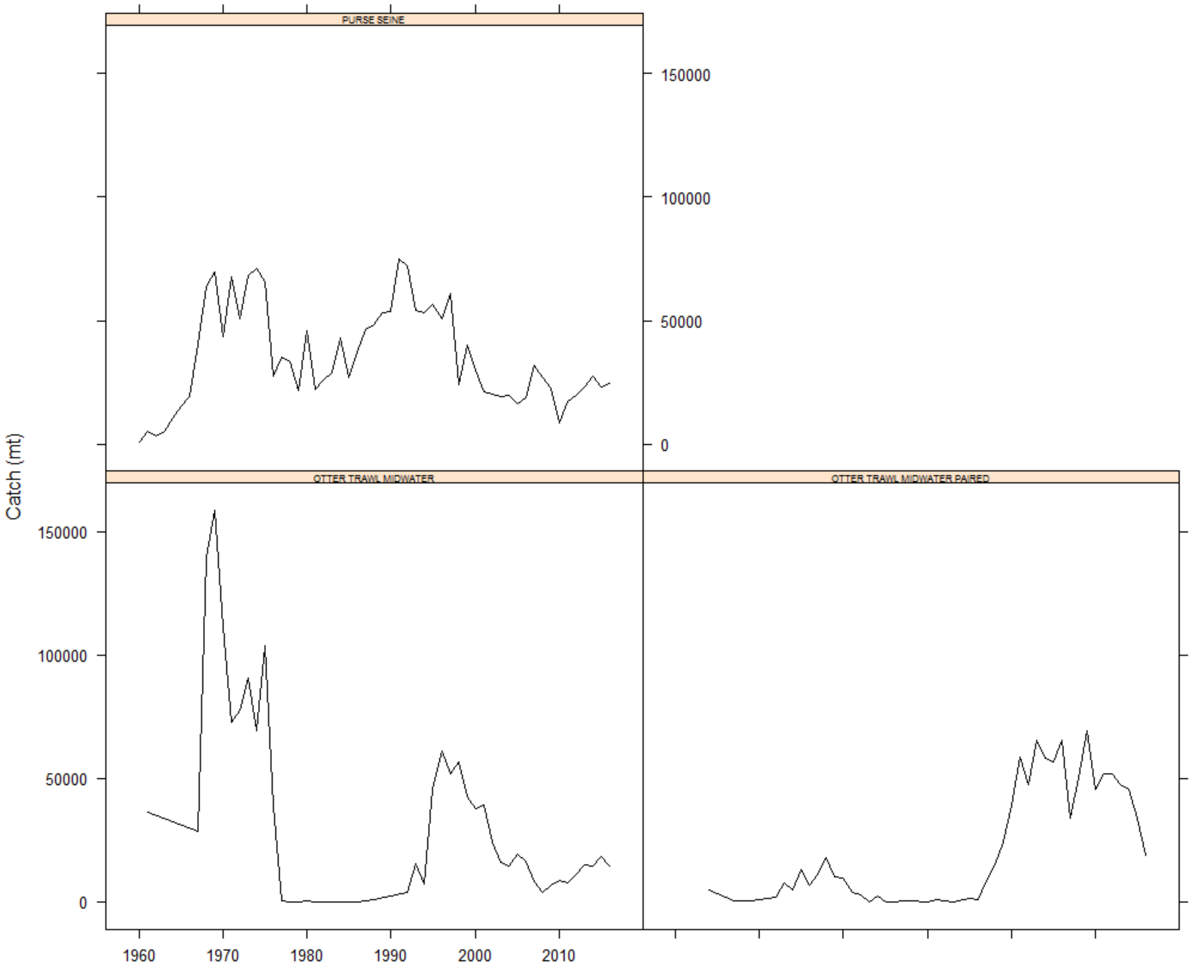


Figure B1- 4 Atlantic herring catch (mt) by mobile and fixed fleets in the Gulf of Maine (GOFM) and outside the GOFM (OTHER)

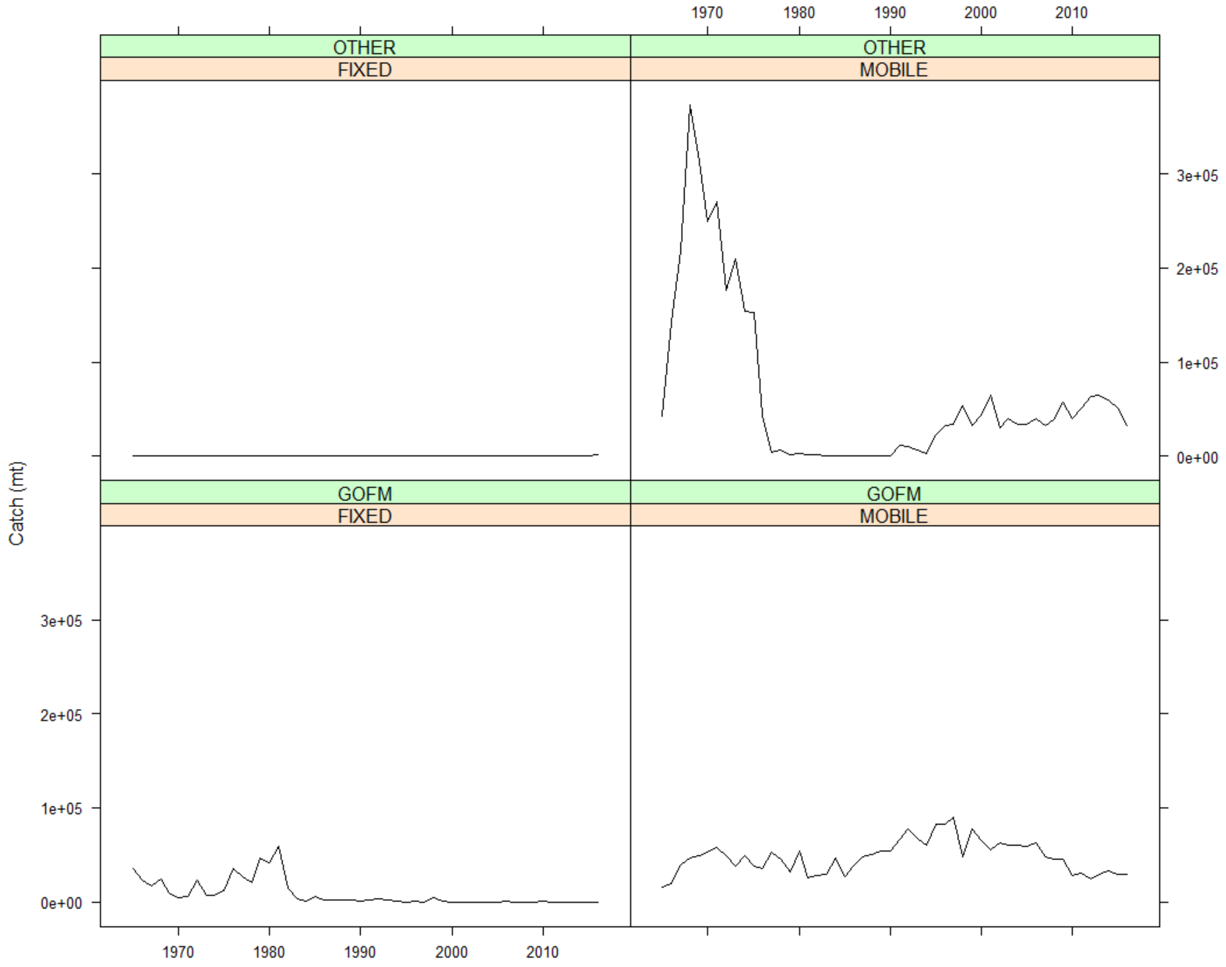


Figure B1- 5 Atlantic herring length composition (cm) of the mobile fleet during 1964-2011 in the Gulf of Maine (GOFM) and all other areas (OTHER)

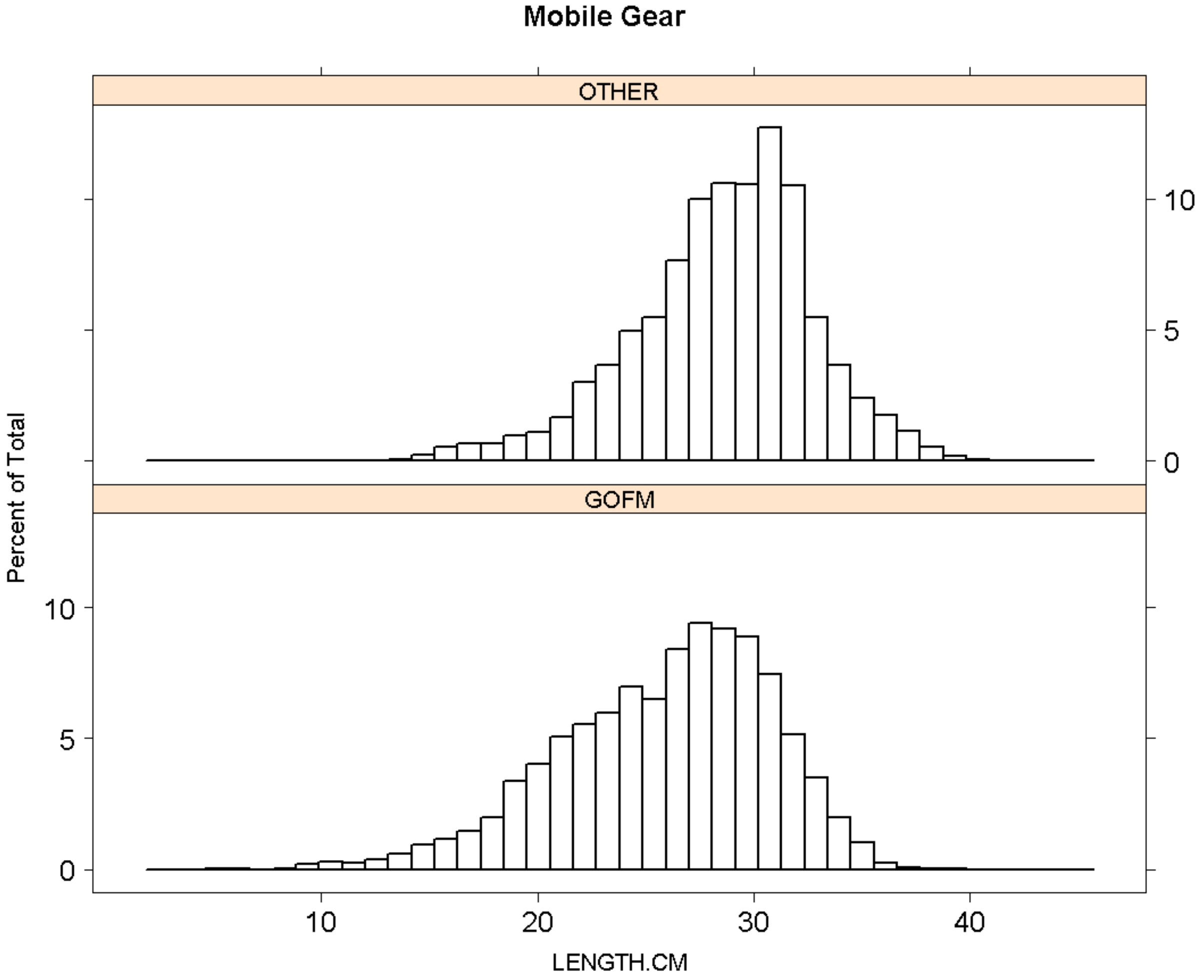


Figure B1- 6 Atlantic herring length composition of the mobile and fixed fleets during 1965-2011 in the Gulf of Maine (GOFM)

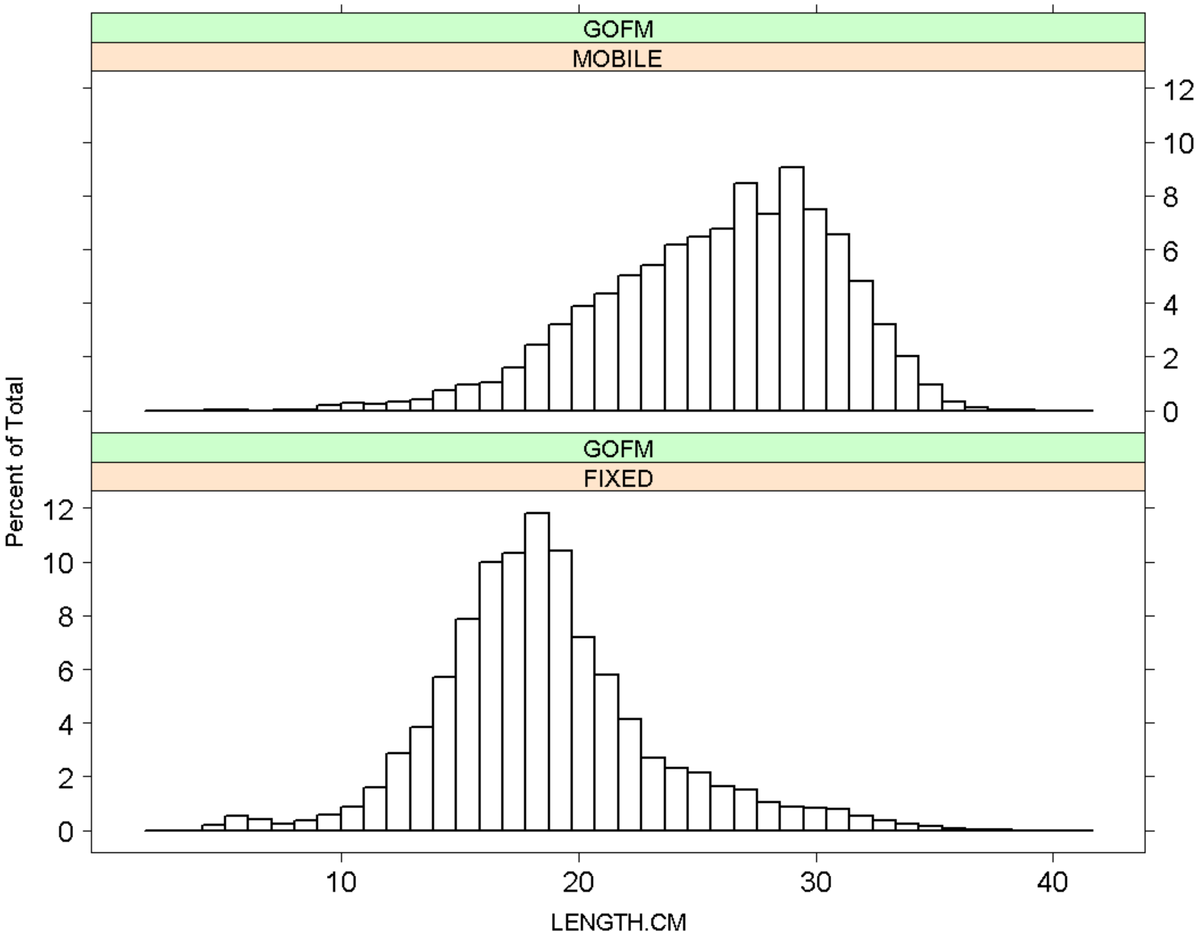


Figure B1- 7 Atlantic herring catch (mt) by the mobile and fixed fleets

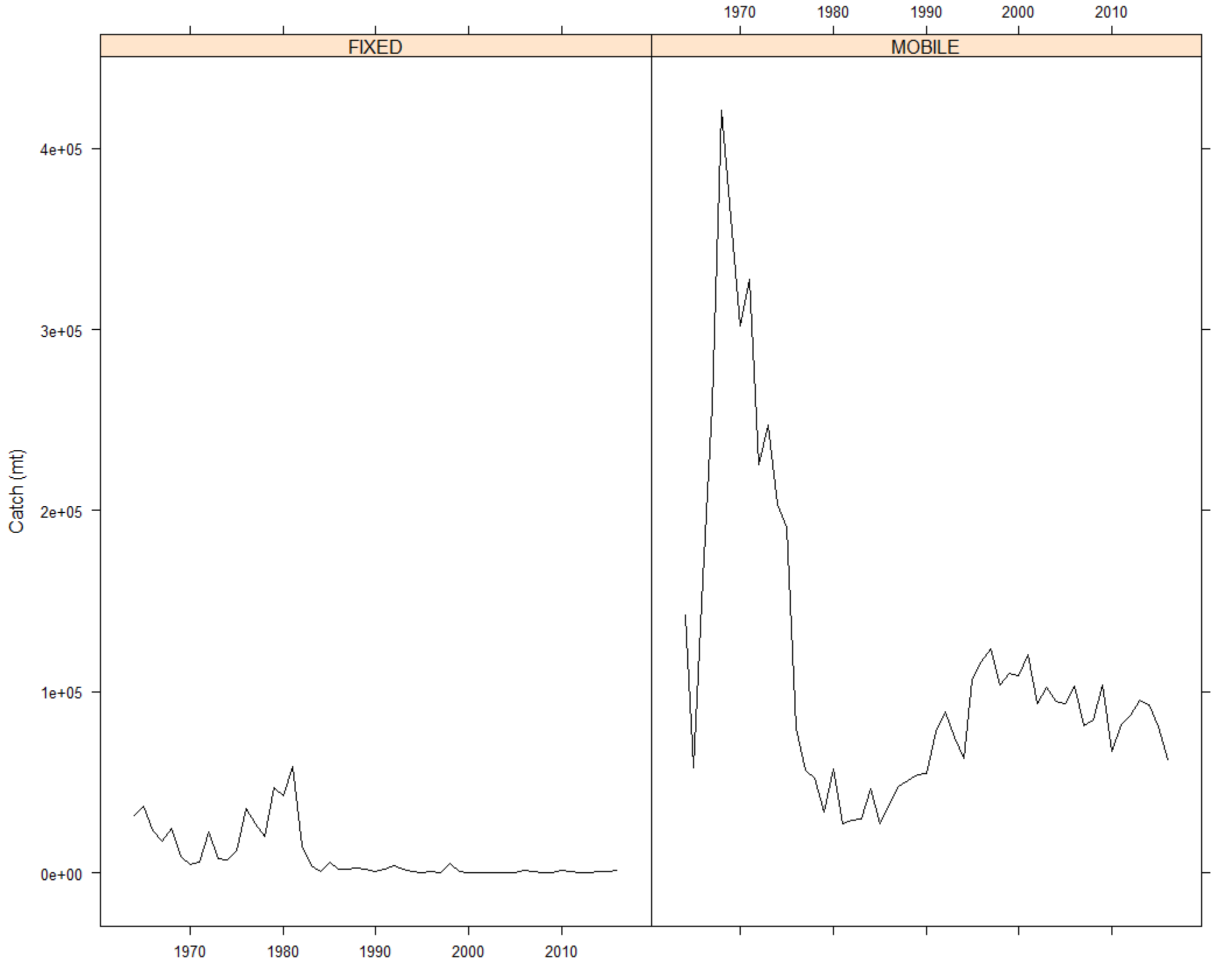


Figure B1- 8 Atlantic herring proportions at age for the mobile fleet

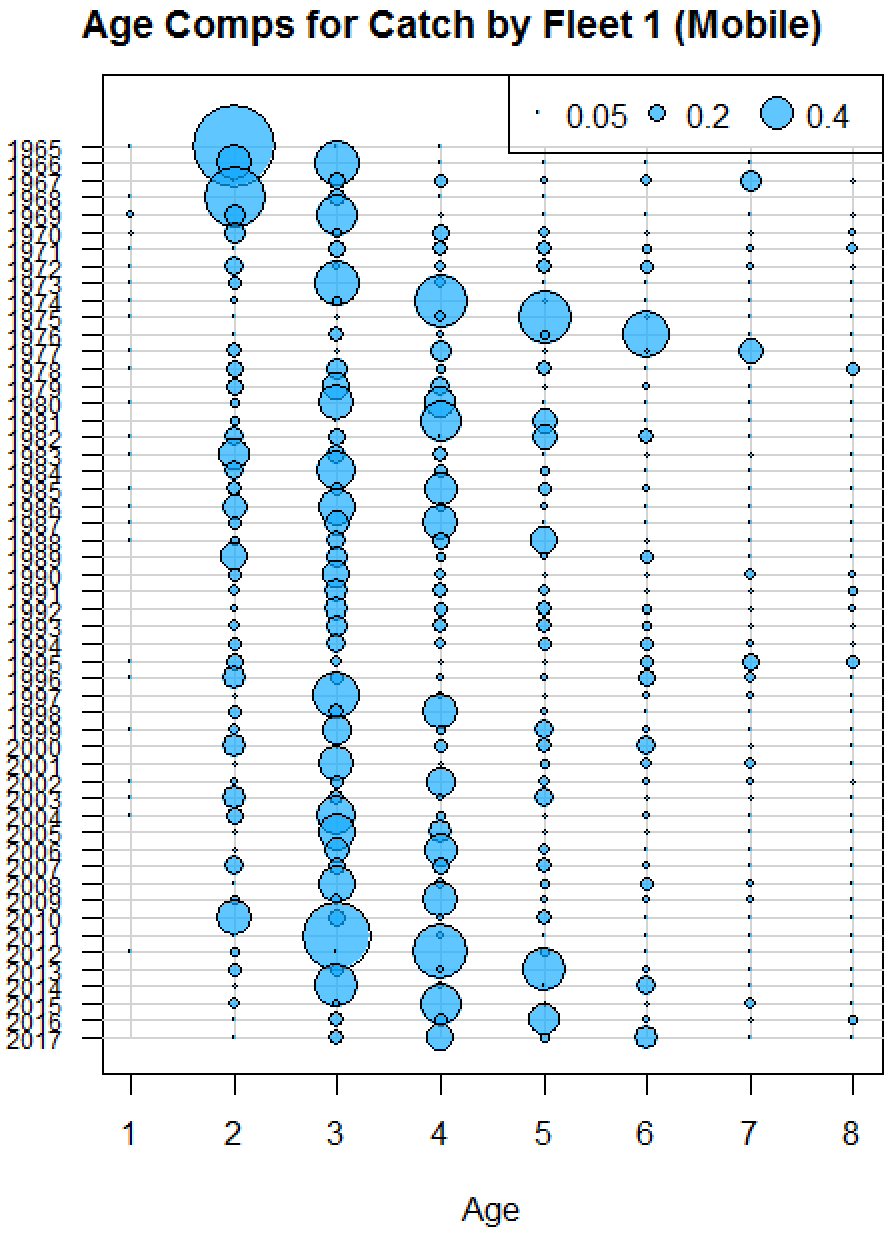


Figure B1- 9 Atlantic herring proportions at age for the fixed fleet

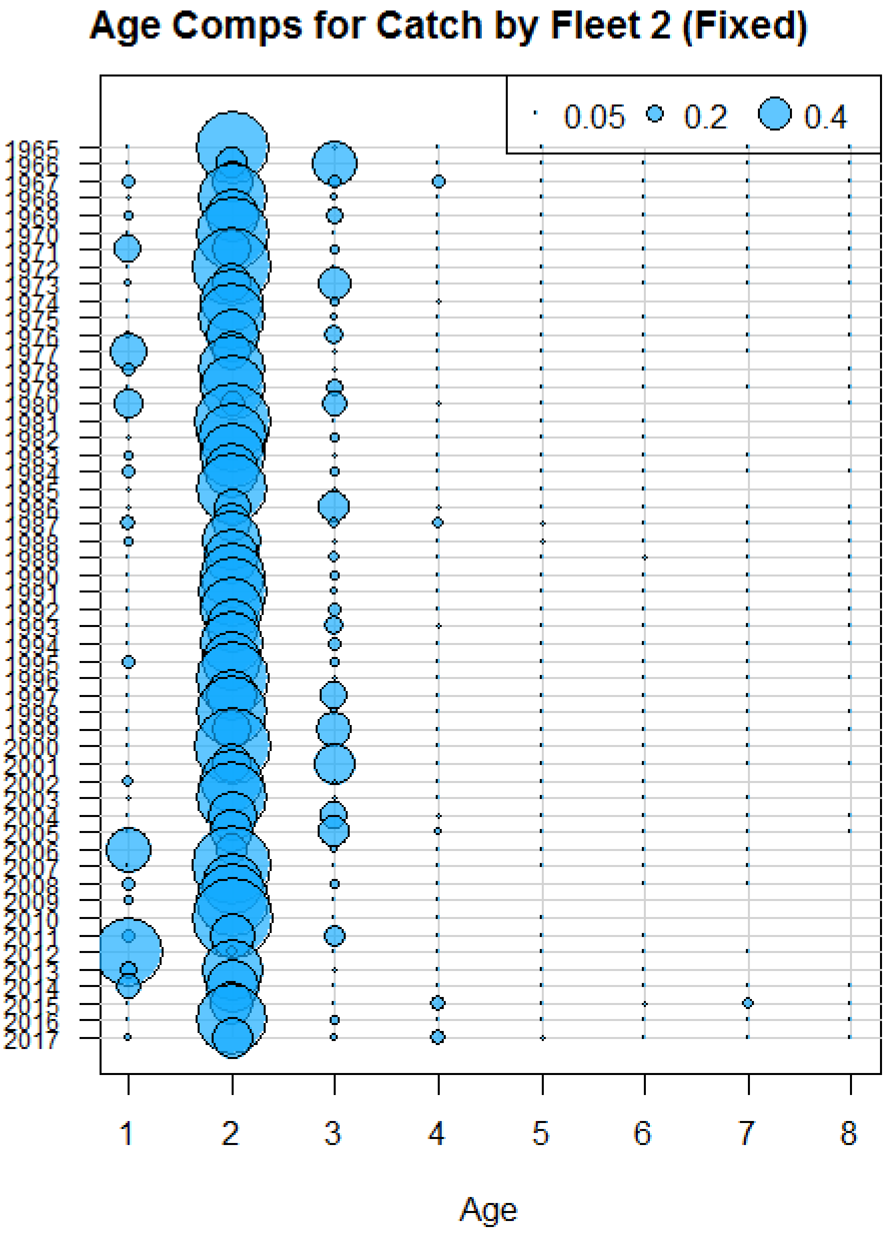


Figure B1- 10 Atlantic herring spawning stock biomass weights (kg) at age

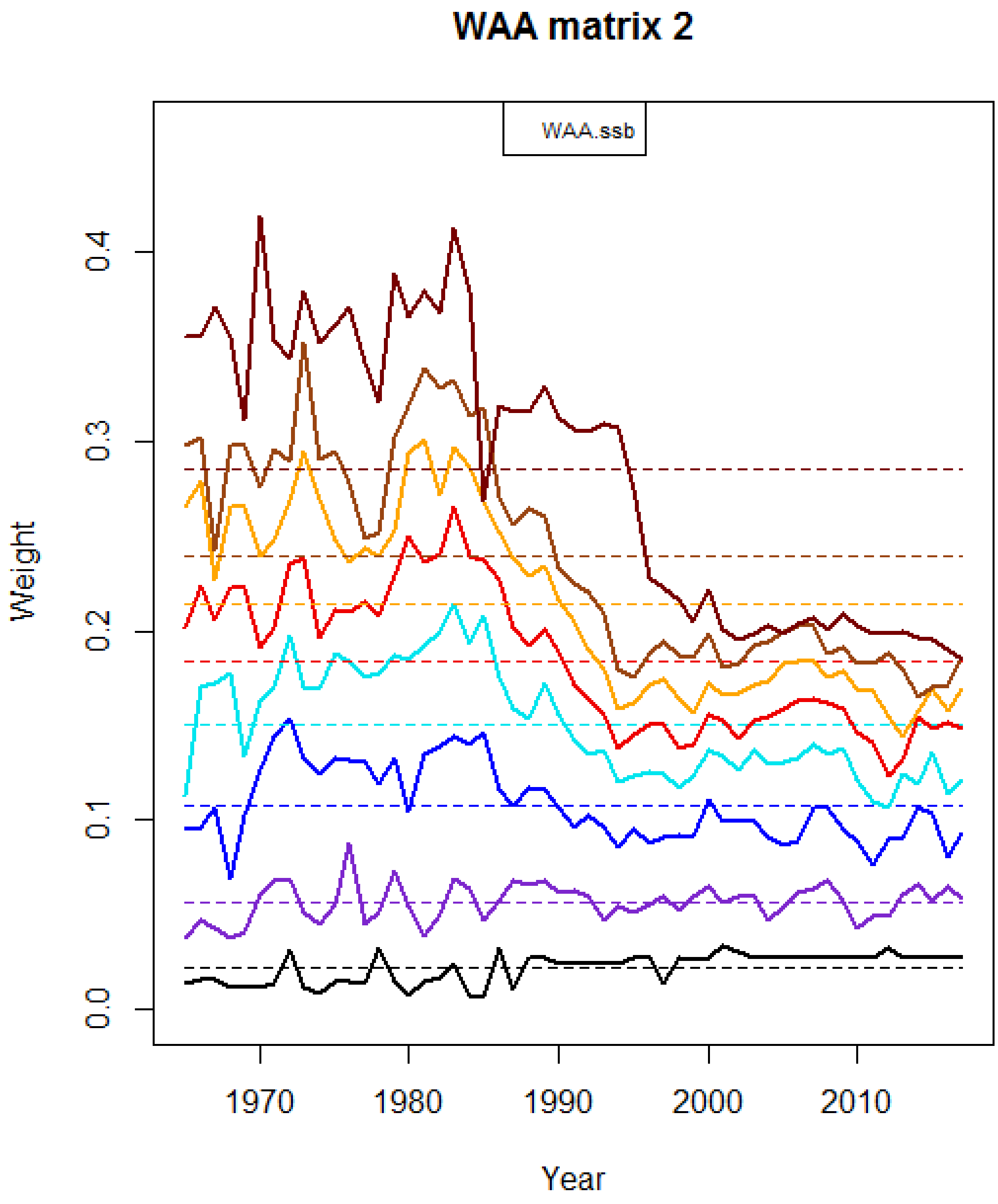
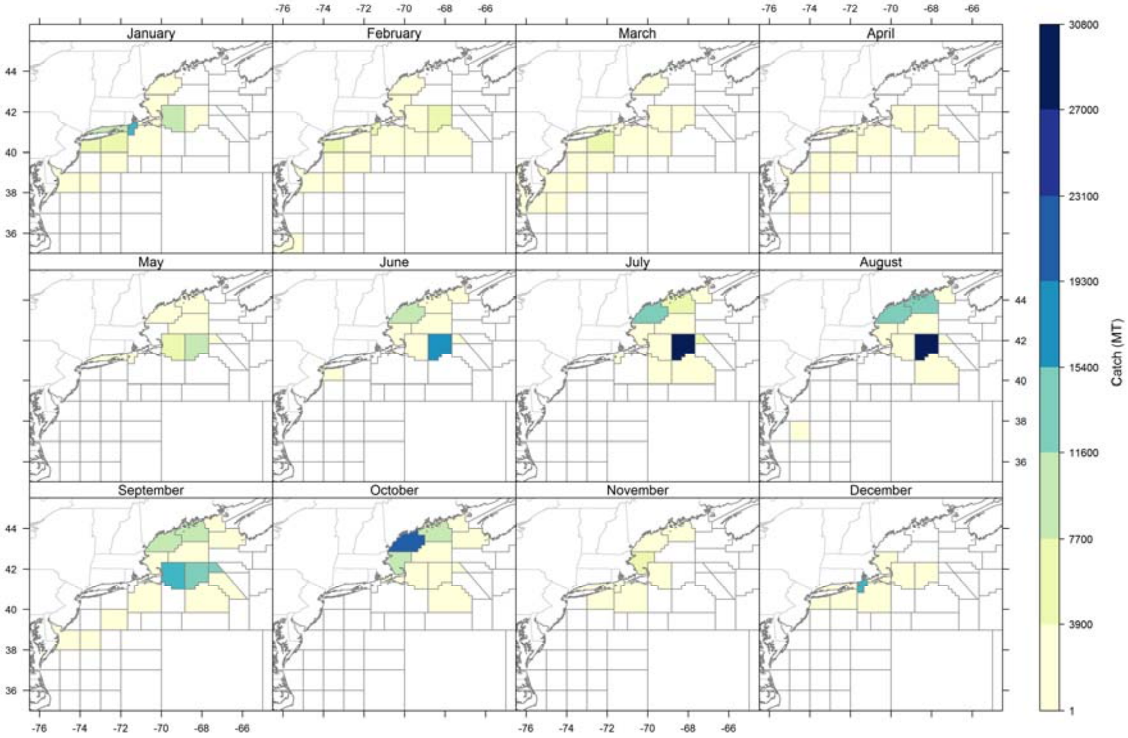
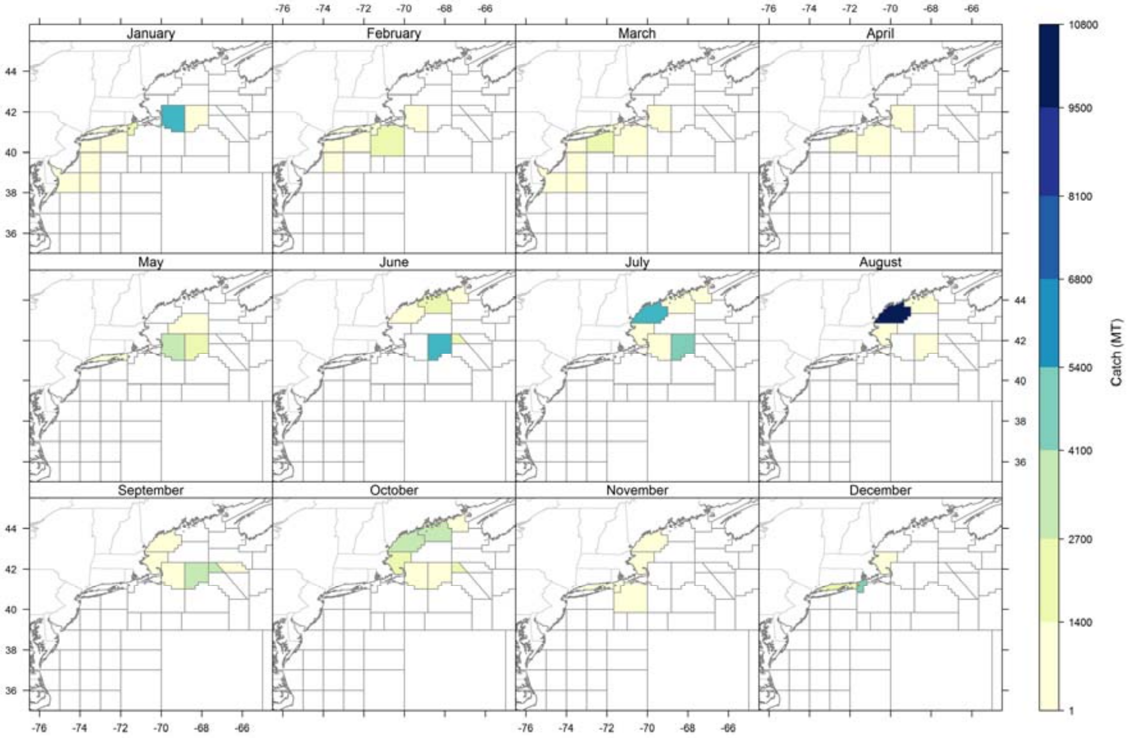


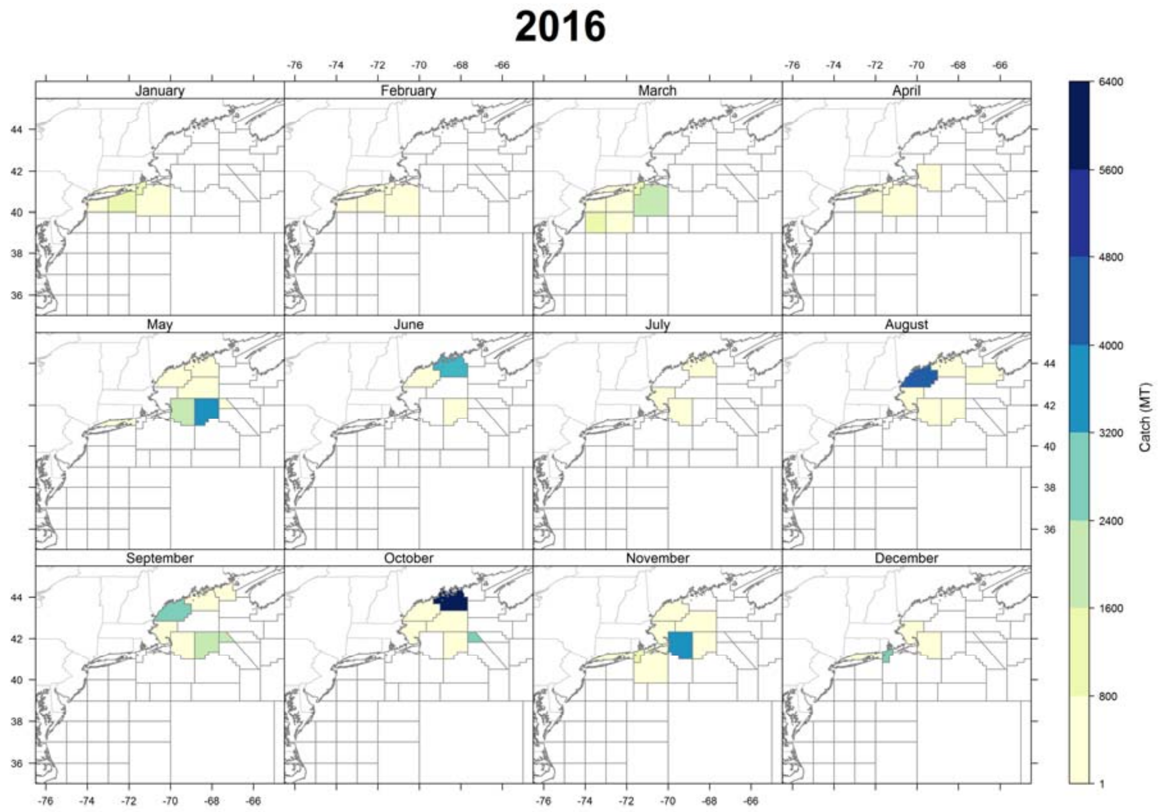
Figure B1- 11 Atlantic herring catch distribution.

2010-2014



2015




2016
January
February
March
April
May
June
July
August
September
October
November
December
-76
-74
-72
-70
-68
-66
44
42
40
38
36
Catch (MT)
6400
5600
4800
4000
3200
2400
1600
800
1

TOR B2: *Present the survey data used in the assessment (e.g., regional indices of abundance, recruitment, state surveys, age-length data, food habits, etc.). Characterize the uncertainty and any bias in these sources of data.*

NMFS bottom trawl surveys

NMFS spring and fall bottom trawl surveys began in 1968 and 1963, respectively, and have continued through 2017. All survey tows in the spring and fall were conducted using the FRV Delaware II, FRV Albatross IV, or FSV Henry B. Bigelow. The Albatross IV was used for most tows in most years prior to 2009. In the spring, however, the Delaware II was responsible for most or all catches in 1973, 1979-1982, 1989-1991, 1994, and 2003. In the fall, the Delaware II was responsible for most or all of the catches in 1977-1978, 1980-1981, 1989-1991, and 1993. The Bigelow has been used exclusively since 2009. To ensure that changes in the indices were more reflective of changes in herring abundance and not due to differences in vessel catchability, Delaware II catches were calibrated to Albatross IV equivalents. Calibration coefficients were based on paired tow experiments (Byrne et al., 1991). Catch numbers from the Delaware II were multiplied by 0.59, and this value was constant among seasons and lengths (Byrne et al. 1991). A range of models used to develop the calibration coefficients for converting Bigelow catches to Albatross IV catches were previously explored and applied in assessment models (Miller et al. 2010; NEFSC 2012). Rather than convert Bigelow catches to Albatross IV equivalents in this assessment, however, the bottom trawl survey index during 2009-2017 (when the Bigelow was used) was treated as a separate survey time series with catchability and selectivity estimated separately from the Albatross IV years. This decision was made because the switch to the Bigelow represents a long-term shift in the survey vessel with known catchability and selectivity differences from previous years. The number of years available for the Bigelow is also now sufficient to estimate relatively precise catchability and selectivity parameters. Treating 2009-2017 as a separate time series was preferred over continued use of the calibration coefficients (Miller et al. 2010; NEFSC 2012) because the calibration coefficients were estimated based on a single year of paired tow experiments and subject to measurement and estimation uncertainties (NEFSC 2012) that are difficult to carry forward into assessment model estimation. Conversely, treating 2009-2017 as a separate time series may allow the estimated difference in catchability to alias other model misspecifications (e.g., the estimated changes in catchability among years may be due to something other than catchability; NEFSC 2008). Thus, while treating 2009-2017 as a separate time series was preferred, assessment models were also run having converted Bigelow catches to Albatross IV equivalents, and these two alternatives were compared and contrasted (see TOR B4). The fall 2017 survey did not cover some survey strata in the mid-Atlantic region (strata 5-12; Figure B2- 1). To account for this inconsistent spatial coverage, a linear regression was fit to the aggregate fall survey indices (arithmetic mean numbers per tow) from 2009-2016 estimated with (dependent variable) and without (independent variable) these strata. This regression was used to calibrate the fall 2017 survey observation (aggregate and at age) to a value assumed equivalent to having sampled the entire survey area. The Working Group noted that the regressions fit to the aggregate indices and indices at age were similar, and that the difference between the uncalibrated and calibrated values (100.9 uncalibrated to 78.6 calibrated) were within the 90%CI of the uncalibrated index. Consequently, this issue was considered relatively inconsequential.

Herring age samples in the spring and fall surveys were collected beginning in 1987. In previous assessments for years prior to 1987, age specific indices were estimated by using age-length keys developed mostly from commercial catch data. Previous assessments, however, have found significant and inexplicable differences in age-length keys from survey and commercial sources and so this practice was abandoned (NEFSC 2012; Appendix B1). Arithmetic mean numbers per tow and associated coefficients of variation in each year were used as indices of Atlantic herring abundance, and age composition since 1987 data was used in assessments Figure B2- 2; Figure B2- 3; Figure B2- 4). As in previous assessments, age-1 survey observations were excluded from the indices because age-1 fish are not selected by the trawl gear, and most observations are thought to be measurement uncertainty as opposed to reflective of changes in herring abundance. Length frequencies were also provided (Figure B2-5).

The trawl doors used on the NMFS spring and fall bottom trawl surveys changed in 1985. Previous assessments have split the spring and fall surveys into separate time series to account for the associated catchability difference caused by the change in trawl doors. This decision was also supported by residual patterns in assessment fit. This practice was continued for this assessment. Ultimately, the spring and fall surveys were each split into three separate series to account for the door change in 1985 and the change to the Bigelow vessel in 2009 (spring: 1968-1984, 1985-2008, 2009-2017; fall: 1963-1984, 1985-2008, 2009-2017).

The NMFS winter survey was conducted during 1992-2007. As in previous assessments, the winter survey was eliminated from consideration as an index of abundance because of concerns over inconsistent spatial coverage among years and lack of fit in previous assessments.

A NMFS summer survey directed at shrimp began in 1983 and has continued through 2017, with the exception of 1984. The spatial extent of this survey is limited to the Gulf of Maine (Figure B2- 6). The working group agreed, however, that fish from the entire complex are mixed in the Gulf of Maine during the summer, and so this survey would be a valid index of the entire stock complex. Age data for Atlantic herring have never been collected on this survey. This survey occurs approximately half way between the spring and fall bottom trawl surveys, however, and so the average of the age-length keys from the spring and fall surveys were used to develop indices at age for the summer survey. Arithmetic mean numbers per tow and associated coefficients of variation in each year were proposed as indices of Atlantic herring abundance (Figure B2- 7; Figure B2- 8). Length frequencies were also provided (Figure B2- 5).

State surveys

Massachusetts Division of Marine Fisheries (MA DMF) spring and fall bottom trawl surveys began in 1977 and have continued uninterrupted through 2017. Joint Maine and New Hampshire spring and fall bottom trawl surveys began in 2001 and 2000, respectively, and have continued uninterrupted through 2017. These surveys cover state waters ≤ 3 nm from shore, and cover a relatively small proportion of the stock, in terms of both spatial coverage and size/age composition. Consequently, the working group agreed that they should not be used for the assessment.

An index from food habits data

An index of herring abundance was developed from stomach contents data collected on the NMFS spring and fall bottom trawl surveys (see TOR B3 for details about stomach contents data collection). The methods were identical to Deroba (2018) and only a brief update and overview were provided here. Data were identical to that in Deroba (2018) except the time series extended through 2016 and some additional observations were added to the years 2012-2014 that had not been previously analyzed. Each stomach observation was essentially treated as a catch-per-effort observation, and a delta approach (hurdle model) was used to develop the index of herring abundance. Separate generalized additive mixed models (GAMMs) were fit to: (i) the amount of herring observed in predator stomachs using only those stomachs in which herring were identified, and (ii) a model of the probability of a stomach containing herring using data from all sampled stomachs. After using a AIC for model selection, the overall best GAMM model for the amount of herring in stomachs with positive herring occurrence included a fixed effect for the product factor of area and season α_{as}, a smooth for predator length $f(l_i)$, and random intercepts for year b_y, predator species m_r, the interaction of year and the product factor of area and season $d_{y,as}$, and the interaction of year, predator species, and the product factor of area and season $g_{y,r,as}$:

$$ln(h_i) = \mu + \alpha_{as} + f(l_i) + b_y + m_r + d_{y,as} + g_{y,r,as} + \varepsilon_i \ .$$

The overall best GAMM model for the probability of a positive herring occurrence included fixed effects for year β_y and the product factor of area and season, smooths for predator length and the amount of herring catch in the tow from which a stomach was sampled $f(c_i)$, and random effects for predator species, and the interaction of predator species and the product factor of area and season $n_{r,as}$:

$$ln\left(\frac{p_i}{(1-p_i)}\right) = \mu + \beta_y + \alpha_{as} + \ f(l_i) + \ f(c_i) + m_r + n_{r,as} \ .$$

An annual index of herring abundance I_y was developed using the year effect coefficients from the GAMM for the amount of herring in stomachs b_y, and the probability of a stomach containing a herring β_y:

$$\hat{h}_y = e^{\mu+b_y};$$

$$\hat{p}_y = \frac{e^{\mu+\beta_y}}{\left(1+e^{\mu+\beta_y}\right)};$$

$$I_y = \hat{h}_y \times \hat{p}_y$$

where μ was the overall model intercept from one of the GAMMs. Estimating measures of uncertainty for this index is not straightforward because methods for combining uncertainty measures from the multistage sampling of the stomachs within the bottom-trawl survey and those from the separate GAMMs have not been developed. Approximate CVs were estimated, however, by summing the year effect variance parameters from each model, and then converting this aggregate variance to a CV for the annual indices of abundance.

The index of abundance was relatively imprecise (Figure B2- 9). The index of abundance was also sensitive to the data used in the GAMM models. Updating the time series through 2016 caused a decrease in the index, mostly in recent years (Figure B2- 10). Eliminating spiny dogfish stomach observations, the most common herring predator in the food habits database, caused a similar change (Figure B2- 11). Removing spiny dogfish had different effects on each of the GAMMs, with the scale of the probability of observing a herring decreasing with the removal of spiny dogfish and the variance among years in the amount of herring in stomachs reducing to near zero (Figure B2- 11). A retrospective analysis of the index of abundance, where one year of data is sequentially dropped from each of the models, was relatively stable (Figure B2- 12). Thus, the models used to derive the index of abundance were insensitive the number of years of data, but relatively sensitive the amount of data contained within each year and throughout the time series. This instability led the Working Group to eliminate the food habits index from consideration in assessment modeling, but assessment sensitivity runs were conducted and further research on this topic was encouraged.

Acoustic index

Water-column acoustic data were collected from 1998 to 2017 during the NEFSC’s autumn stratified-random survey along the continental shelf from Cape Hatteras, North Carolina to Canadian waters in the Gulf of Maine (Figure B2- 13). Details of acoustic data acquisition, processing, and post-processing are detailed in Jech and Michaels (2006), Jech and Stroman (2012), Jech (2014), and Jech and Sullivan (2014) but a brief description is provided here.

All echosounders and frequencies were calibrated prior to each survey, and usually near the completion of the cruise using the standard target method (Foote et al., 1987). Transducers were calibrated using either copper (Cu) or tungsten carbide with 6% cobalt binder (WC) spheres, depending on year and conditions. For Cu spheres, a 64-mm diameter Cu sphere was used to calibrate the 18-kHz echosounders, a 60-mm Cu sphere was used to calibrate the 38-kHz echosounders, and a 23-mm Cu sphere was used to calibrate the 120-kHz echosounders. The 38.1-mm diameter WC was used to calibrate the 18, 38, 70 and 200-kHz echosounders.

Water-column acoustic data during the stratified-random bottom survey were collected continuously as the vessel transited between randomly-located trawl-haul sites and during all deployments (Figure B2- 13). Trawl locations were selected randomly within bathymetrically-defined strata for each cruise (Azarovitz et al., 1997). The sampling order was selected by minimizing travel time among trawl locations, thus while locations were random, the order was not. Data from 1998-2005 were collected on the NOAA ship *Albatross IV* (hereafter *Albatross IV*). Data collected from 2009-2012 were collected on the NOAA ship *Henry B. Bigelow* (hereafter *Bigelow*). Data collected during 2007-2008 were collected on both vessels as part of inter-ship comparison surveys (Miller et al., 2010). No data were collected in 2006 and data in 2010 were collected only to 50 m, thus were not used for analysis. An EK500 echosounder collected 12, 38, and 120-kHz data on the *Albatross IV* from 1998-2002. In 2003, the EK500 was replaced with 18-, 38-, and 120-kHz EK60 echosounders. The 12-kHz single-beam, and 18, 38, and 120-kHz split-beam transducers were located downward-looking on the keel. The *Bigelow* collected acoustic data from EK60 echosounders operating at 18, 38, 120, and 200 kHz from 2007-2012 and a 70 kHz EK60 echosounder was added in 2009. Beam angles were 16^o for the 12 kHz, 11^o for the 18 kHz, and 7^o for all other frequencies. The *Albatross IV*'s EK500 was calibrated in 1996, March 2001, and April 2002. The *Albatross IV*'s EK60 was calibrated in 2008, just before decommissioning. Gain settings for years without calibrations were applied from years with calibrations (Jech, 2014). The *Bigelow*'s EK60s were calibrated in spring 2007, and then immediately prior to each survey from 2008-2012. All calibrations followed protocols set from the systematic survey. *Bigelow* 38-kHz gain settings were very stable with ±0.1 dB variation over the calibrations.

Multi-frequency volume backscatter (S_v, dB·re 1 m^{-1}) data were post-processed and classified as described in Jech and Michaels (2006) and Jech (2014) using Myrix Echoview software (v8+; GPO Box 1387 Hobart, Tasmania, Australia, www.echoview.com). Briefly, echograms were scrutinized to remove acoustic and electrical noise, erroneous seafloor detections, data shallower than 10 m, and data deeper than 0.5 m above the sea floor. When 12 or 18, 38, and 120-kHz data were available, the indices of the echogram pixels that contained S_v values greater than -66 dB in all three frequencies were mapped to the 38-kHz echogram and that echogram was used to visually classify Atlantic herring. In cases where only one or two frequency data were available, a modified version of the methods described in Jech and Michaels (2006) was applied (Jech, 2014).

Visual scrutiny of the acoustic data from the stratified-random survey sometimes suggested the presence of Atlantic herring in the water column, but the species composition of the bottom trawl catch co-located or in the immediate vicinity of the acoustic data did not support apportioning acoustic backscatter to Atlantic herring (e.g., Figure B2- 14). In these cases, these aggregations were scrutinized as “unverified” Atlantic herring and used to evaluate the level of uncertainty in examining acoustic data collected during the stratified-random surveys.

After the S_v data were scrutinized for Atlantic herring, area backscattering, also known as nautical area scattering coefficient (NASC, m^2 nmi^{-2}; MacLennan et al. 2002), attributable to Atlantic herring, was generated by vertically integrating throughout the water column and horizontally averaging into 0.5 nmi elementary distance sampling units (EDSU). Geographical location, date, and time were associated with each s_A value. The final water-column data were 38-kHz s_A data classified as Atlantic herring s_A in 0.5 nmi EDSU. Data analyses were done in QGIS (QGIS Development Team, 2018), R statistical package (R Core Team, 2015), and PBS Mapping (Schnute et al., 2004).

The mean s_A ($\overline{s_A}(S_f, y)$) and standard deviation ($SD(S_f, y)$) were calculated annually for each finfish stratum (S_f) for a subset of offshore finfish strata (OS_f) where only offshore strata that had at least one occurrence of acoustic backscatter classified as Atlantic herring among the years were used (Figure B2- 15; Figure B2- 16; Figure B2- 17):

$$\overline{s_A}(S_f, y) = \frac{1}{N(S_f, y)} \sum_{i=1}^{N(S_f,y)} s_A(i) \qquad (1),$$

where the number of s_A values within each stratum were different among stratum and among years (y), and all s_A values were used regardless of activity, i.e., data during steaming and trawls were included. Those mean s_A values for each stratum and year were used to calculate a stratum-area (A_{S_f}) weighted mean ($\overline{s_A}(y)$) and variance ($Var(y)$) for each year:

$$\overline{s_A}(y) = \sum_{j=1}^{M} \frac{A_{S_f}(j)}{A_{OS_f}} \overline{s_A}(j, y) \qquad (2),$$

$$Var(y) = \sum_{j=1}^{M} \left[\left(\frac{A_{S_f}(j)}{A_{OS_f}} \right)^2 \frac{SD_j(S_f, y)^2}{N_j(S_f, y)} \right] \qquad (3),$$

where there were M = 49 offshore strata used in this analysis, j indexes strata, and A_{OS_f} is the total area (nmi^2) of all 49 offshore strata. Table B2- 1 provides the mean and variance estimates for the offshore strata from 1998 to 2017.

Table B2- 1 Stratum-area weighted mean ($\overline{s_A}(y)$) and variance ($Var(y)$) estimates for the offshore strata where acoustic backscatter was classified as Atlantic herring for each year.

Year	Mean	Var
1998	114.85	344.14
1999	78.04	23.84
2000	191.80	2726.22
2001	112.21	120.15
2002	113.92	123.23
2003	33.83	33.05
2004	117.57	1048.22
2005	33.76	11.56
2007	33.08	71.00
2007	32.55	25.76
2008	4.54	0.27
2008	40.74	17.41
2009	52.74	22.92
2011	41.50	76.18
2012	64.65	38.43
2013	51.76	13.61
2014	93.05	68.06
2015	44.15	8.42
2016	40.48	4.54
2017	37.68	19.90

Figure B2- 1 NMFS offshore bottom trawl survey strata

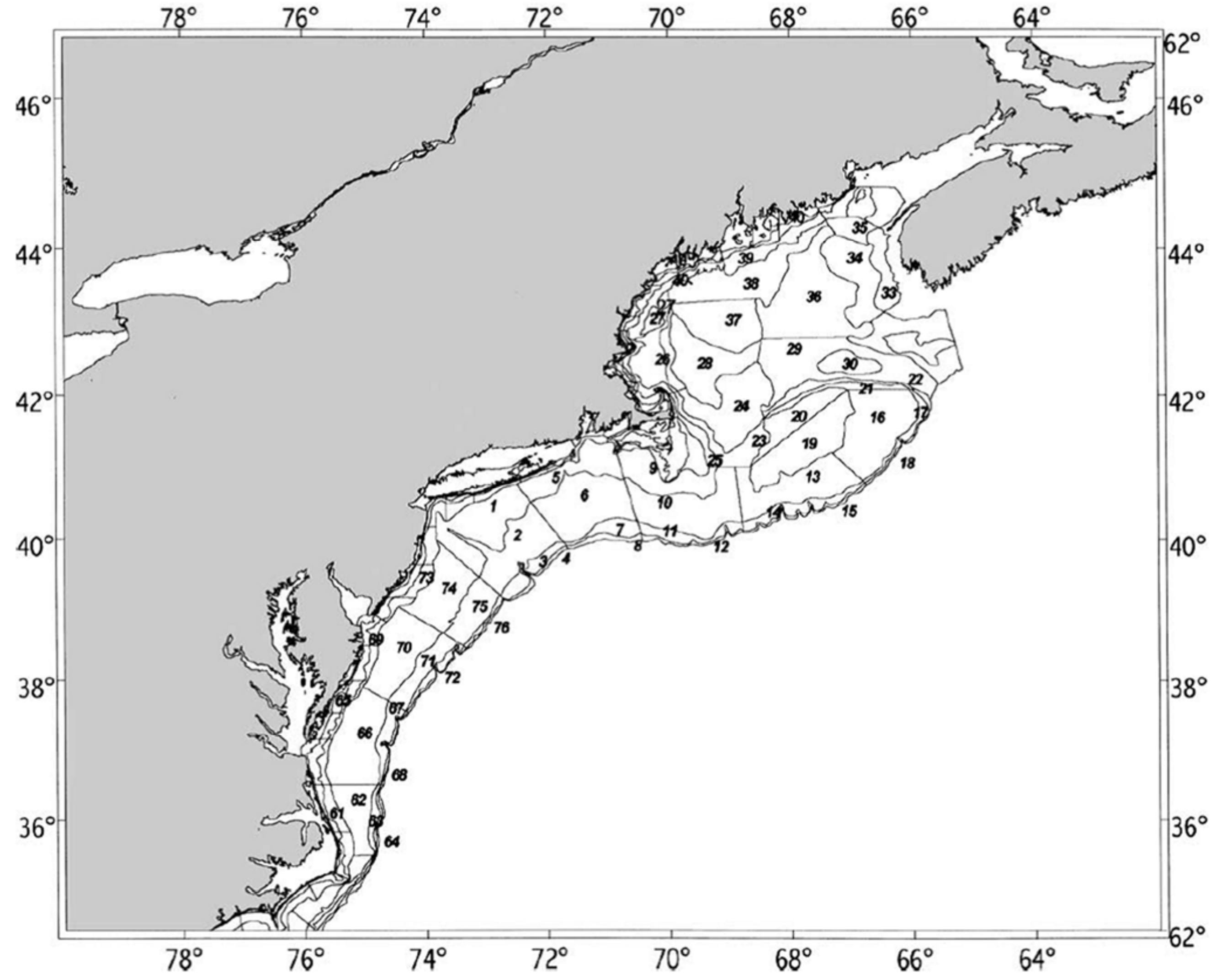
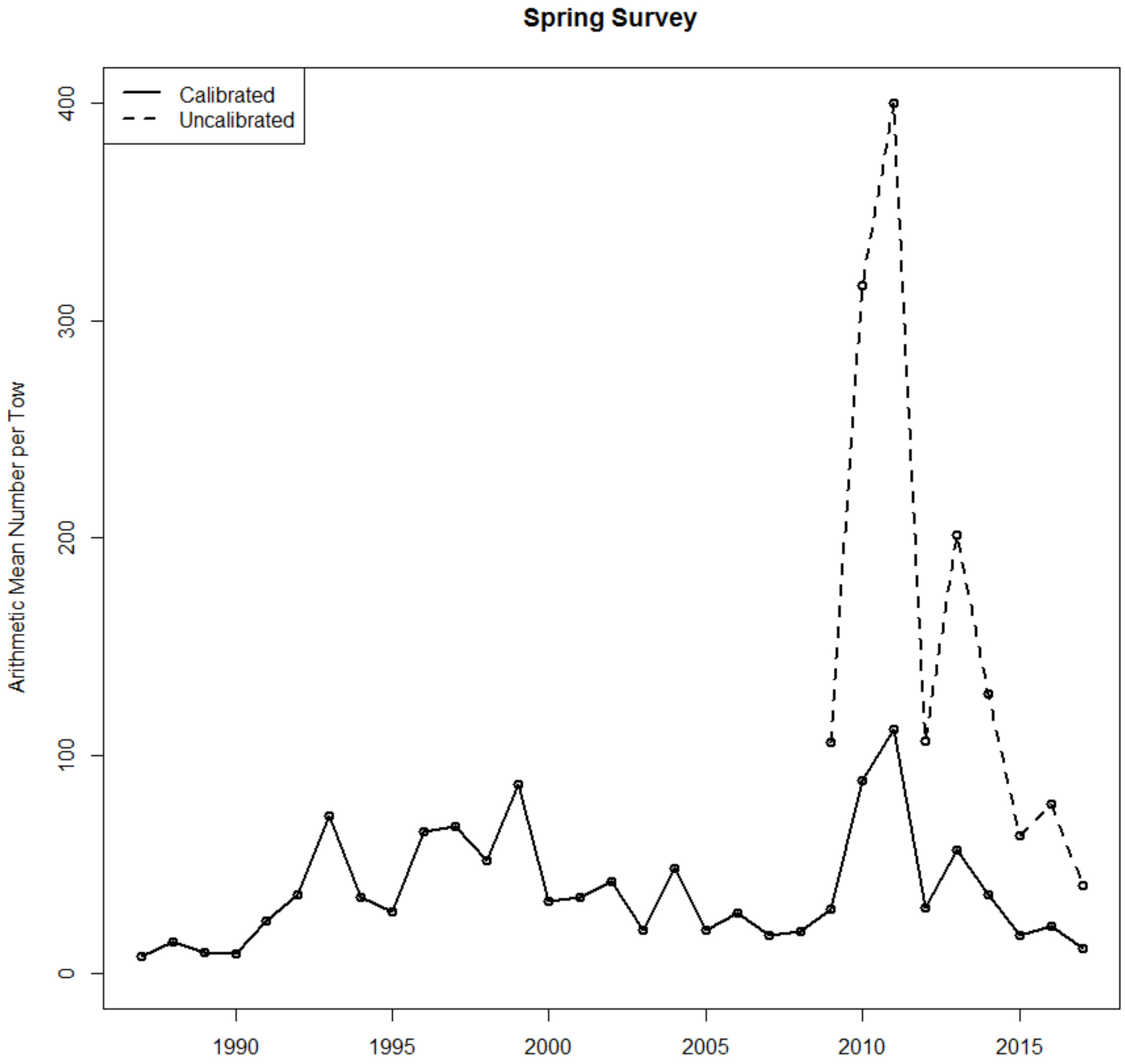


Figure B2- 2 Time series of NMFS spring bottom trawl survey Atlantic herring abundance indices with and without 90%CI.



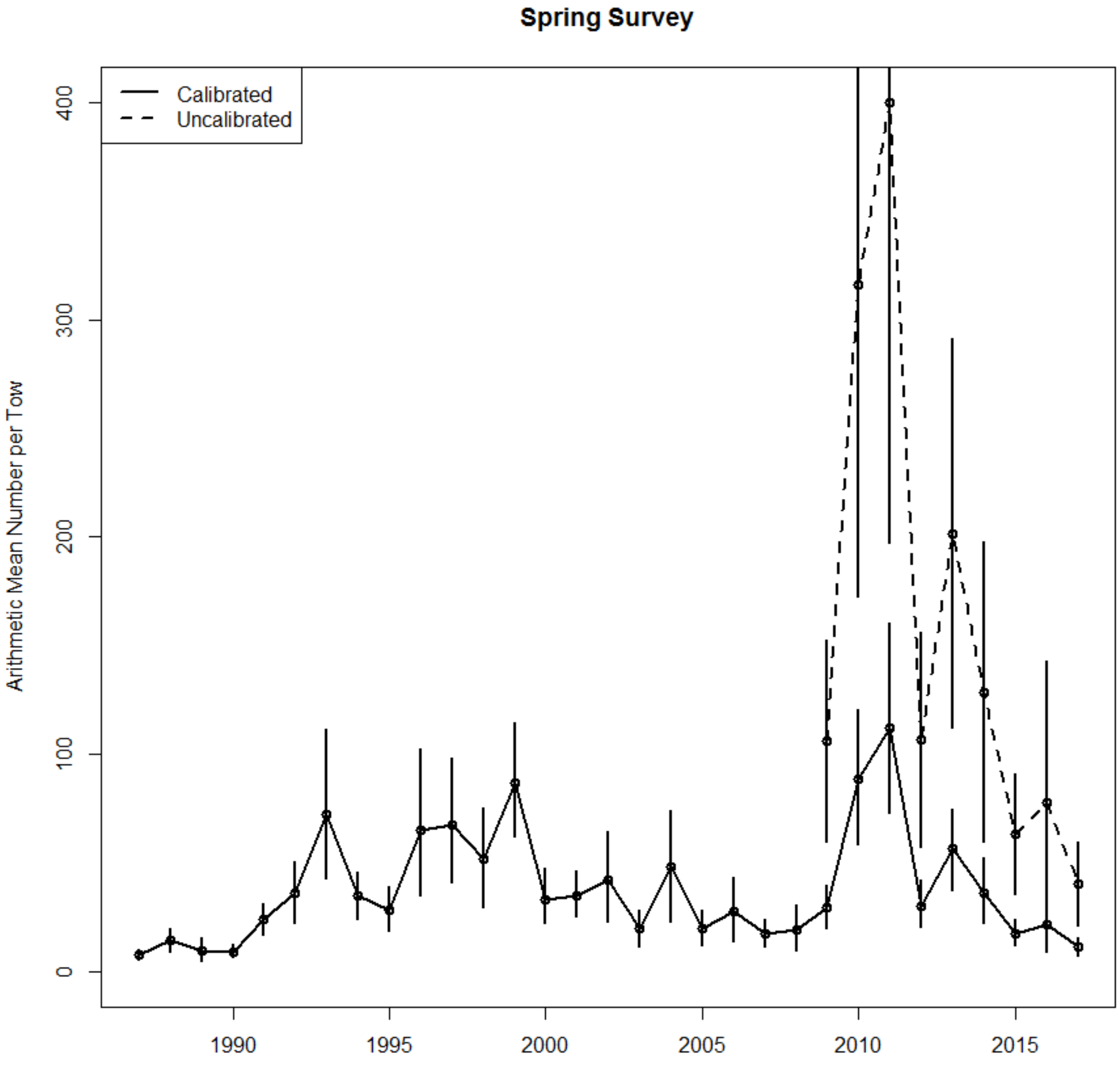
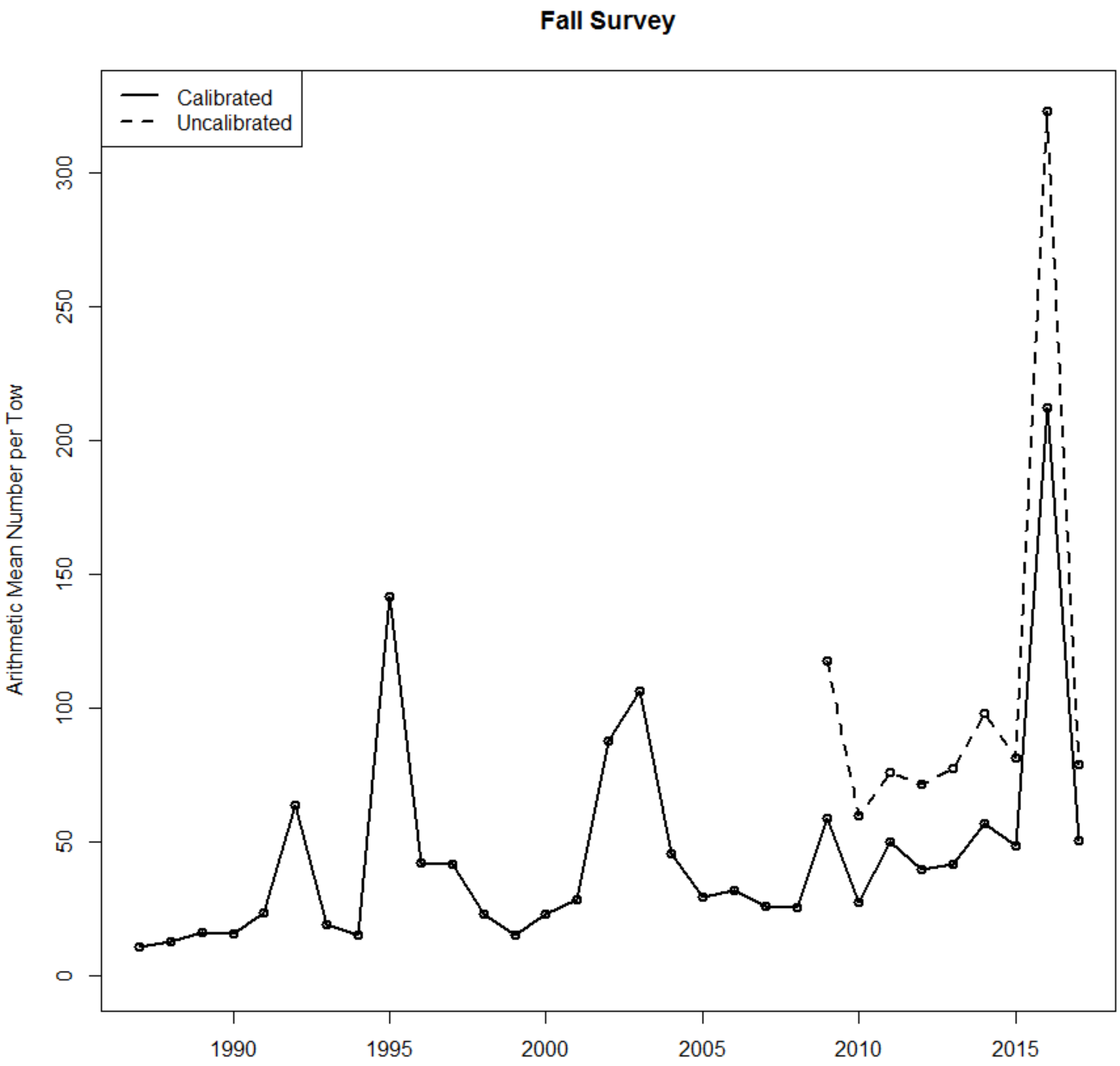

Spring Survey
Calibrated
Uncalibrated
Arithmetic Mean Number per Tow
0
100
200
300
400
1990
1995
2000
2005
2010
2015

Figure B2- 3 Time series of NMFS Fall bottom trawl survey Atlantic herring abundance indices with and without 90%CI



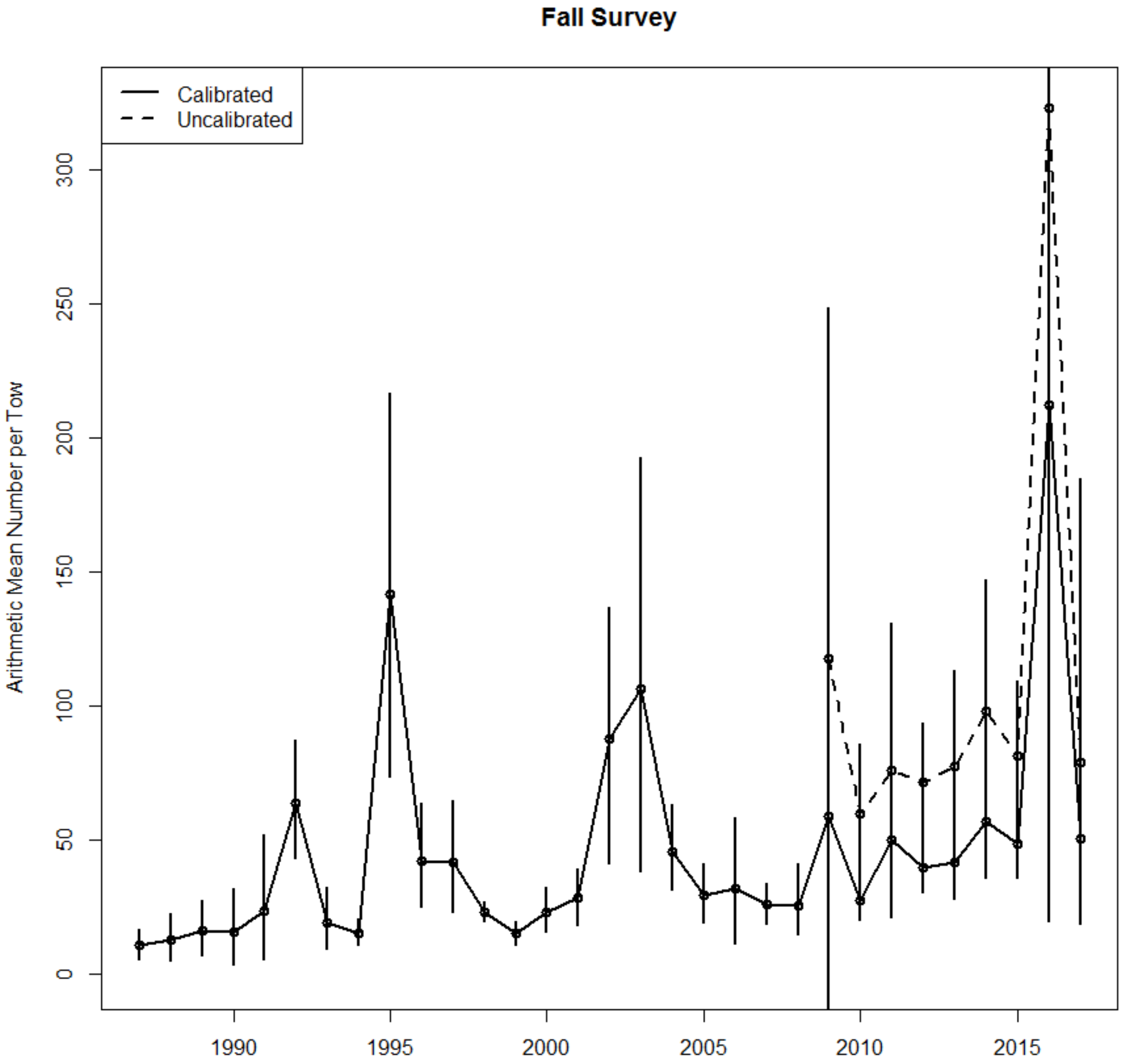
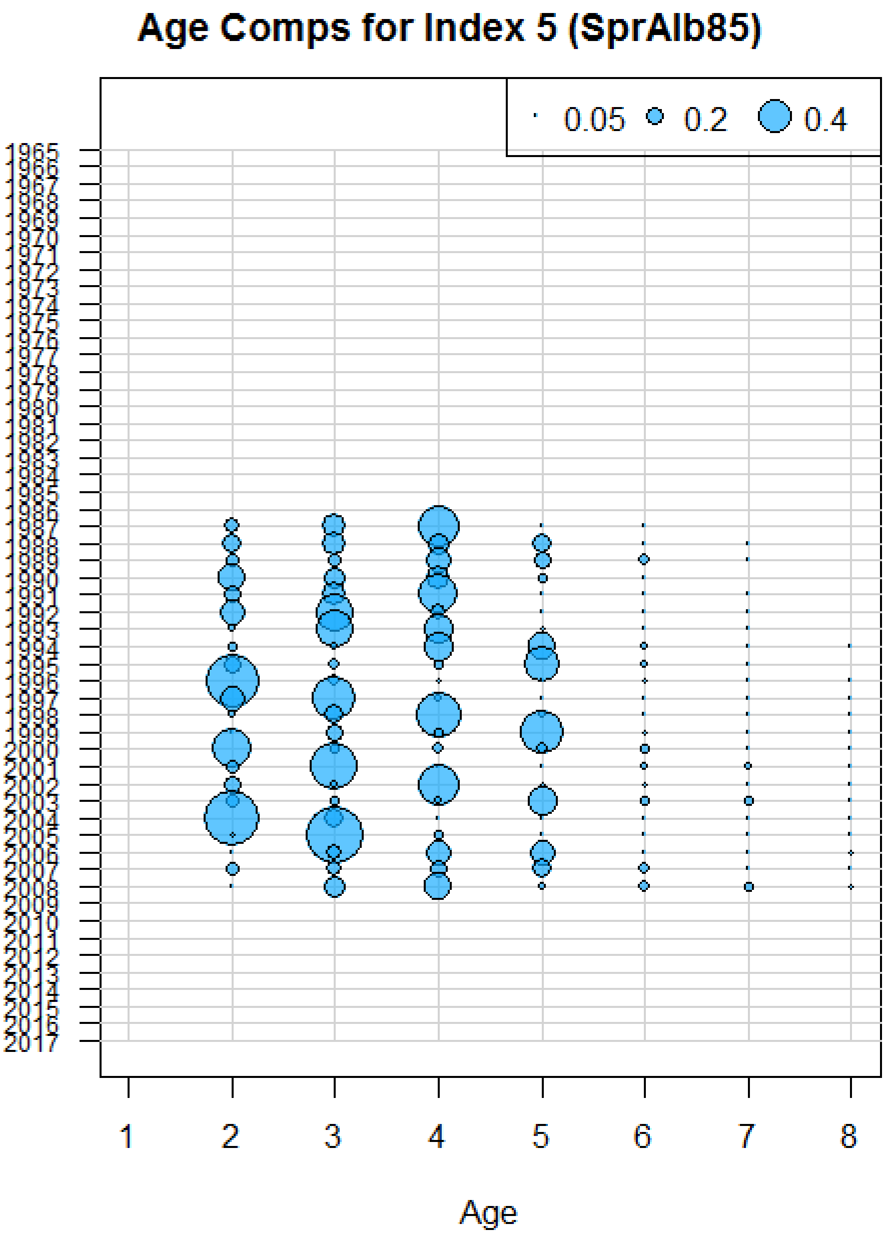
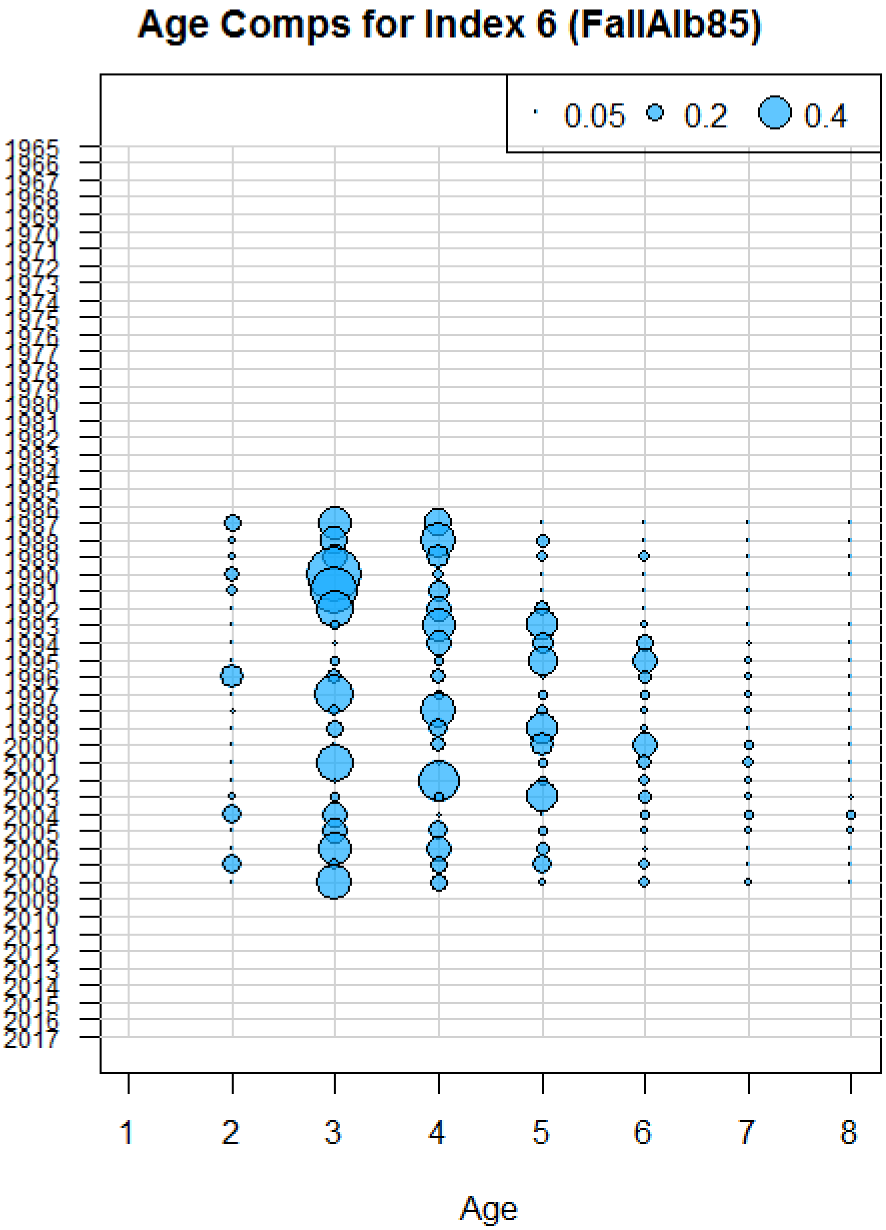
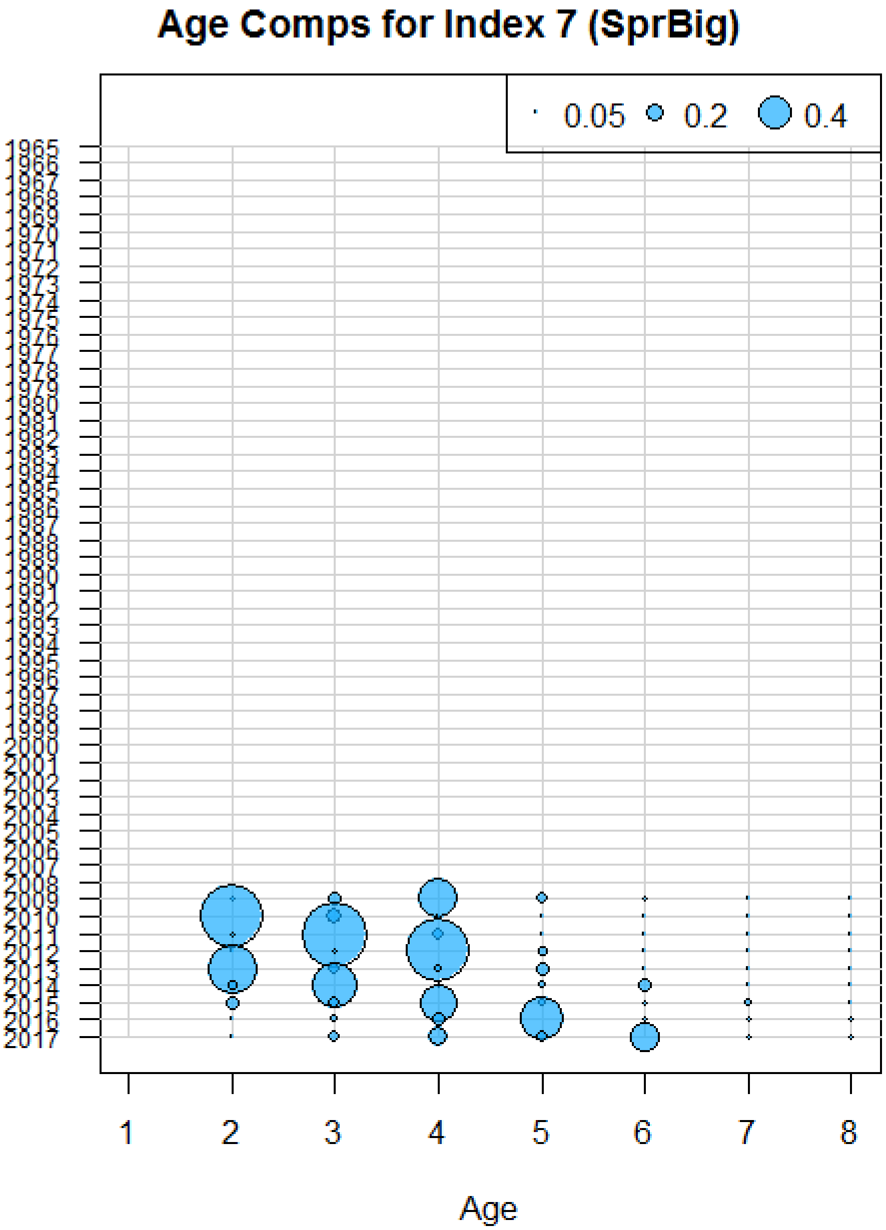

Fall Survey
Calibrated
Uncalibrated
Arithmetic Mean Number per Tow
0
50
100
150
200
250
300
1990
1995
2000
2005
2010
2015

Figure B2- 4 Atlantic herring proportions at age for the spring Albatross years (SprAlb85), spring Bigelow years (SprBig), fall albatross years (FallAlb85), and fall Bigelow years (FallBig)




Age Comps for Index 6 (FallAlb85)
0.05
0.2
0.4
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
1
2
3
4
5
6
7
8
Age


Age Comps for Index 7 (SprBig)
0.05
0.2
0.4
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
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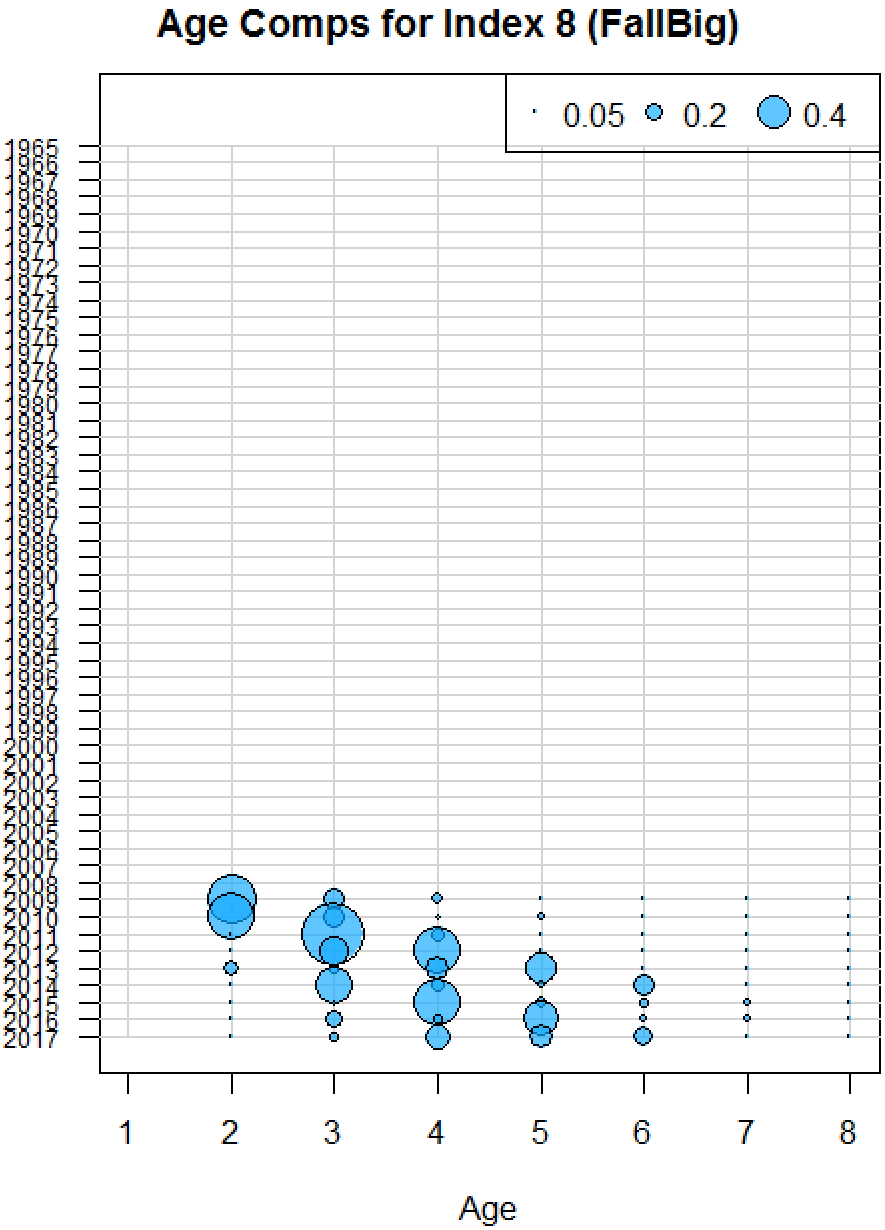
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
1
2
3
4
5
6
7
8
Age


Age Comps for Index 8 (FallBig)
0.05
0.2
0.4
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
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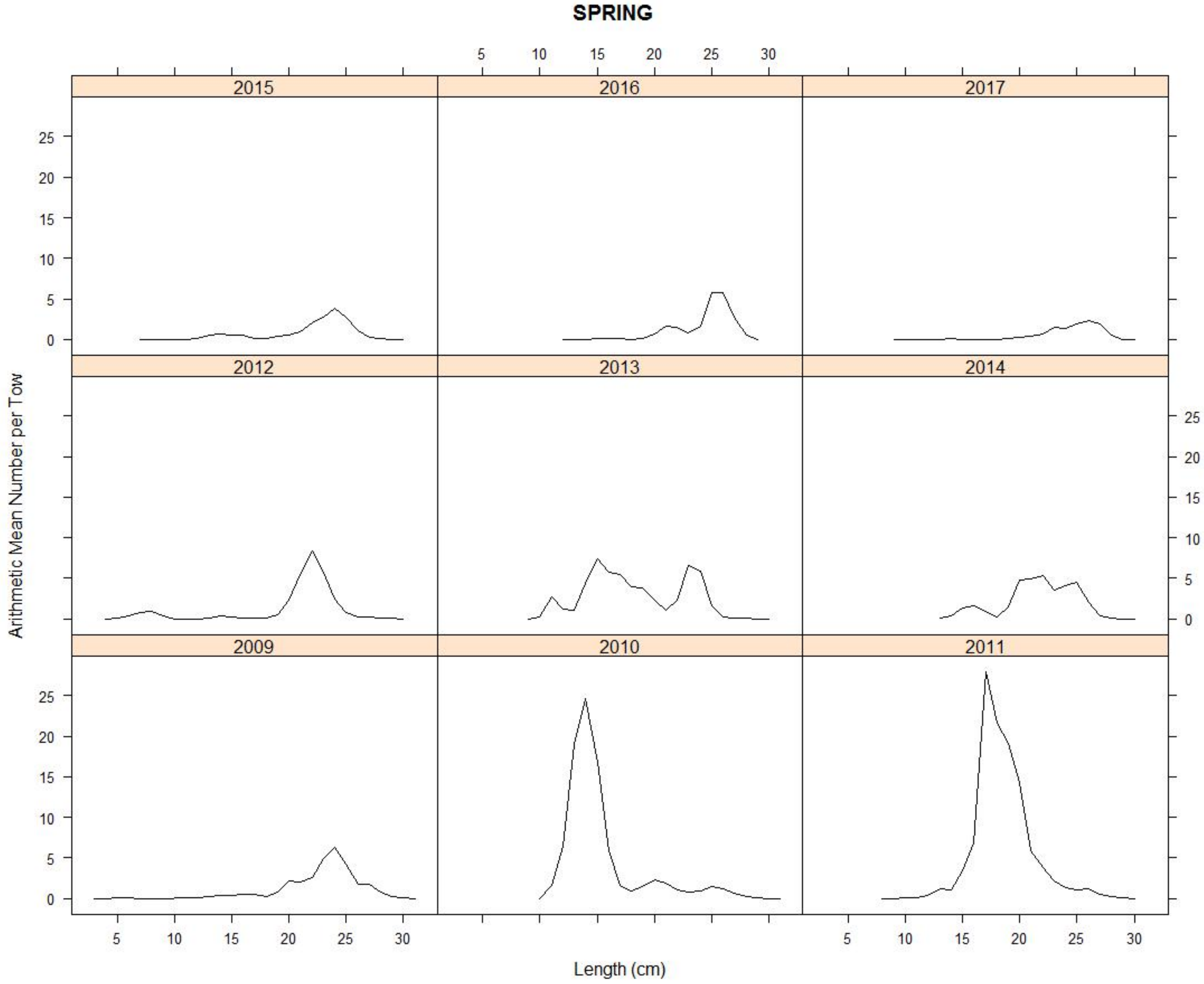
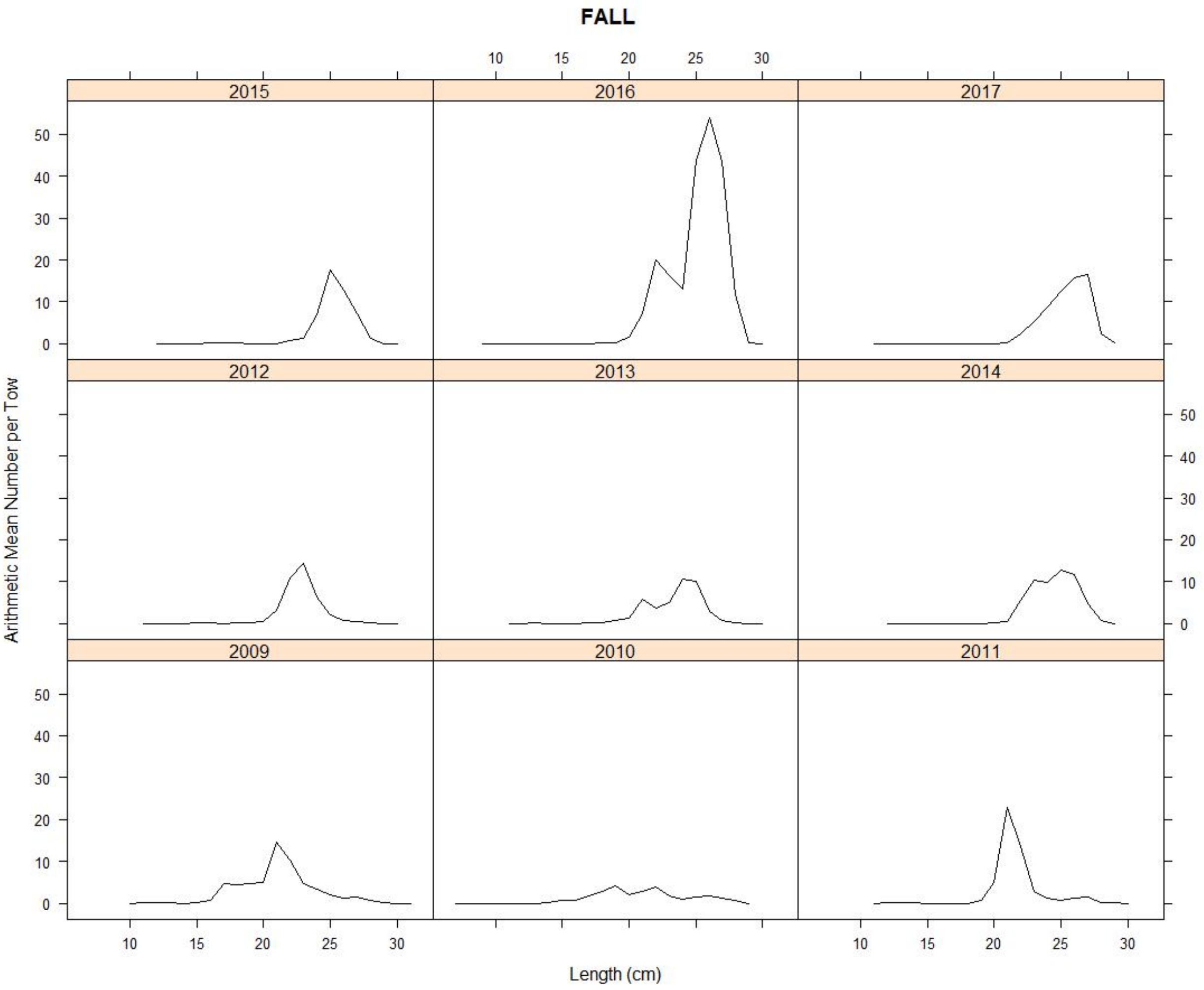
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
1
2
3
4
5
6
7
8
Age

Figure B2- 5 Atlantic herring length frequency from NMFS spring, fall, and summer (shrimp) bottom trawl surveys




FALL
2015
2016
2017
2012
2013
2014
2009
2010
2011
Arithmetic Mean Number per Tow
Length (cm)
0
10
20
30
40
50
10
15
20
25
30

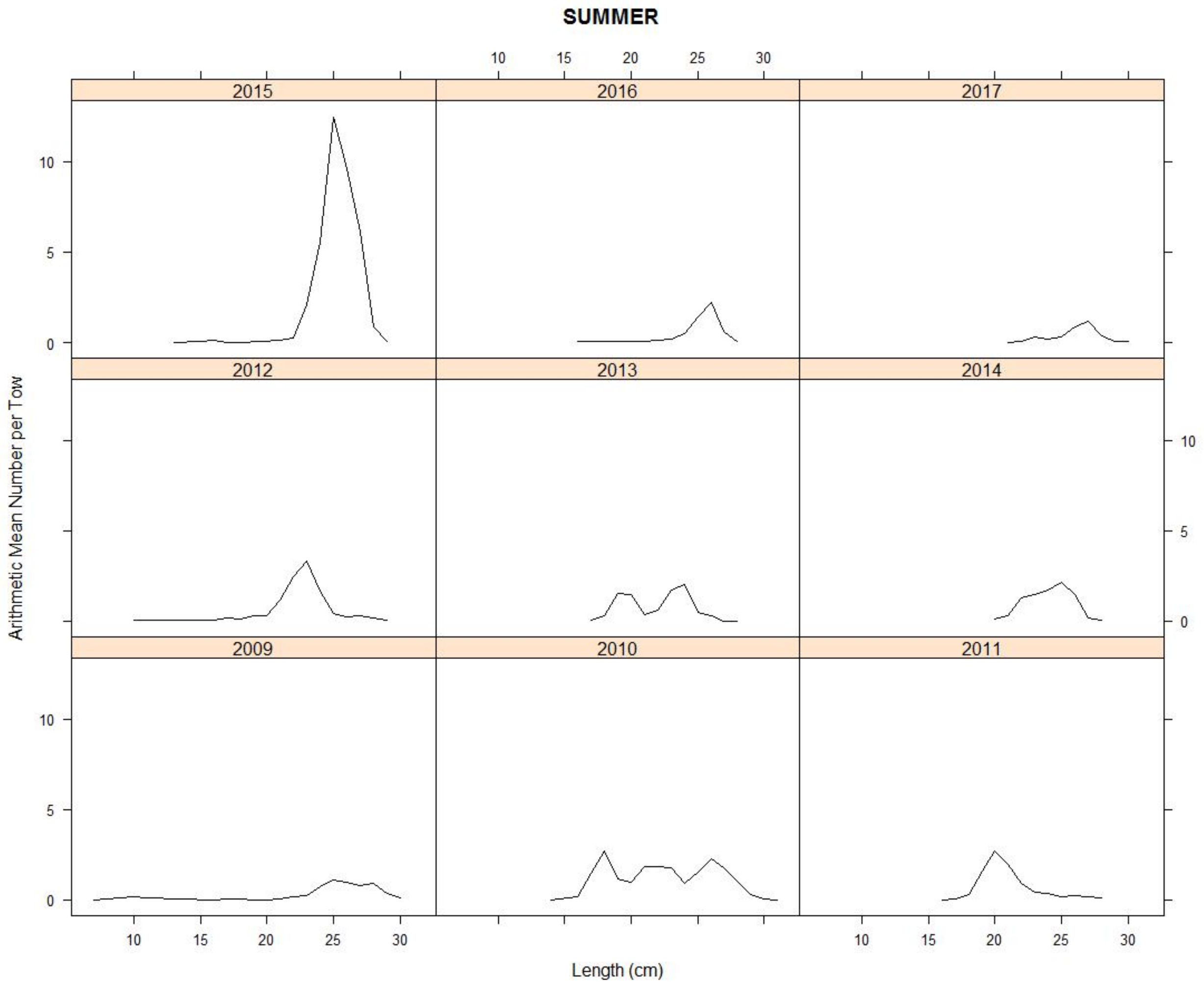

SUMMER
2015
2016
2017
2012
2013
2014
2009
2010
2011
Arithmetic Mean Number per Tow
Length (cm)
0
5
10
10
15
20
25
30

Figure B2- 6 Location of tows taken during the NMFS summer (shrimp) survey 1983-2017.

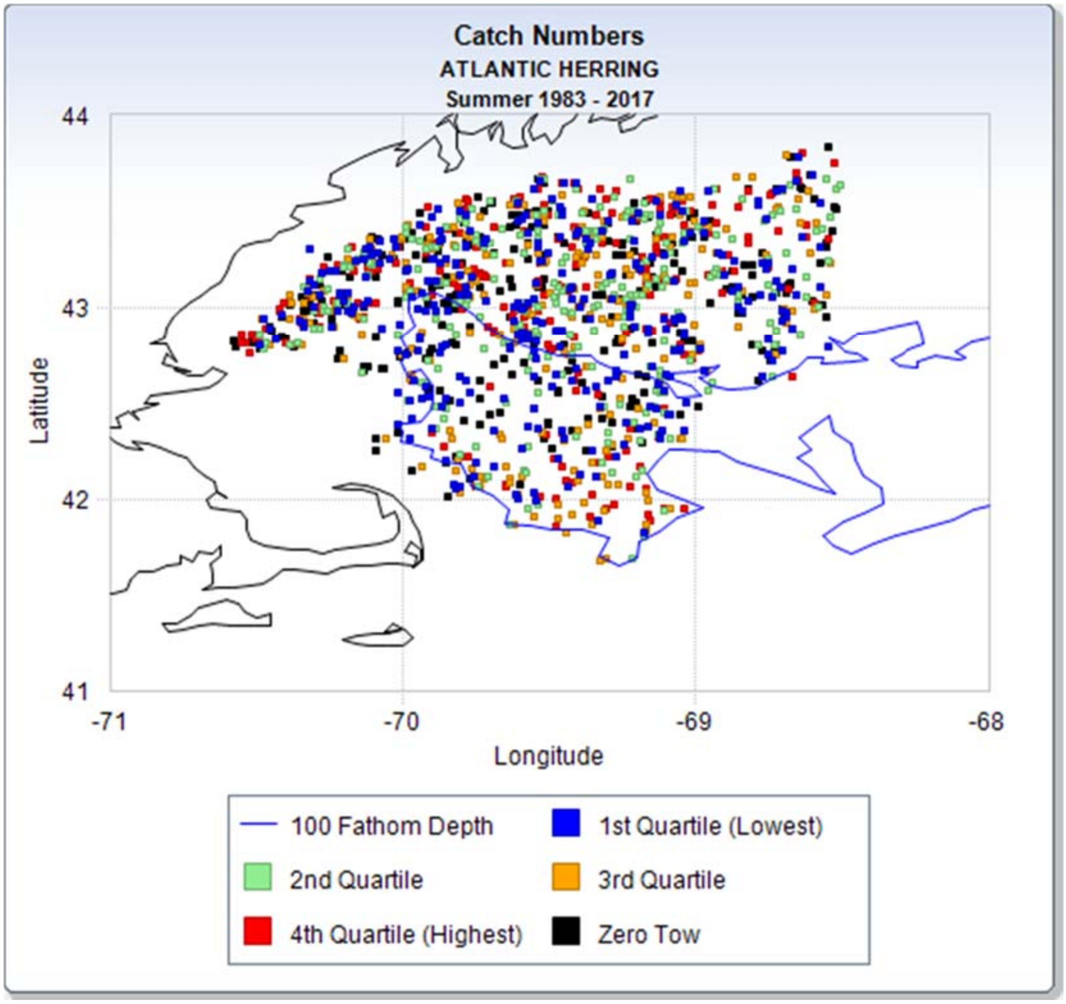


Figure B2- 7 Summer NMFS bottom trawl survey abundance index time series for Atlantic herring with 90%CI

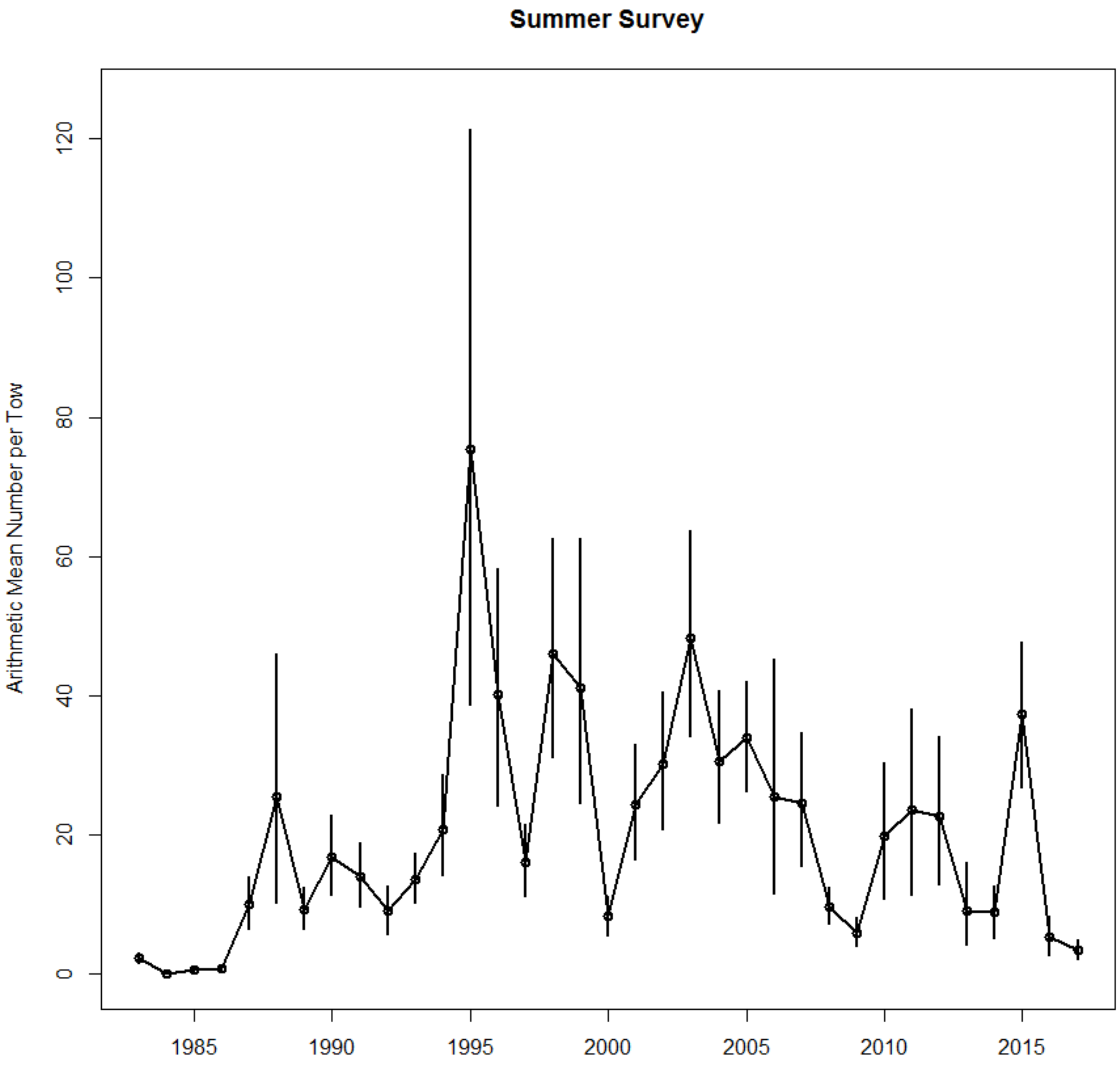


Figure B2- 8 Atlantic herring proportions at age from the NMFS summer (shrimp) survey.

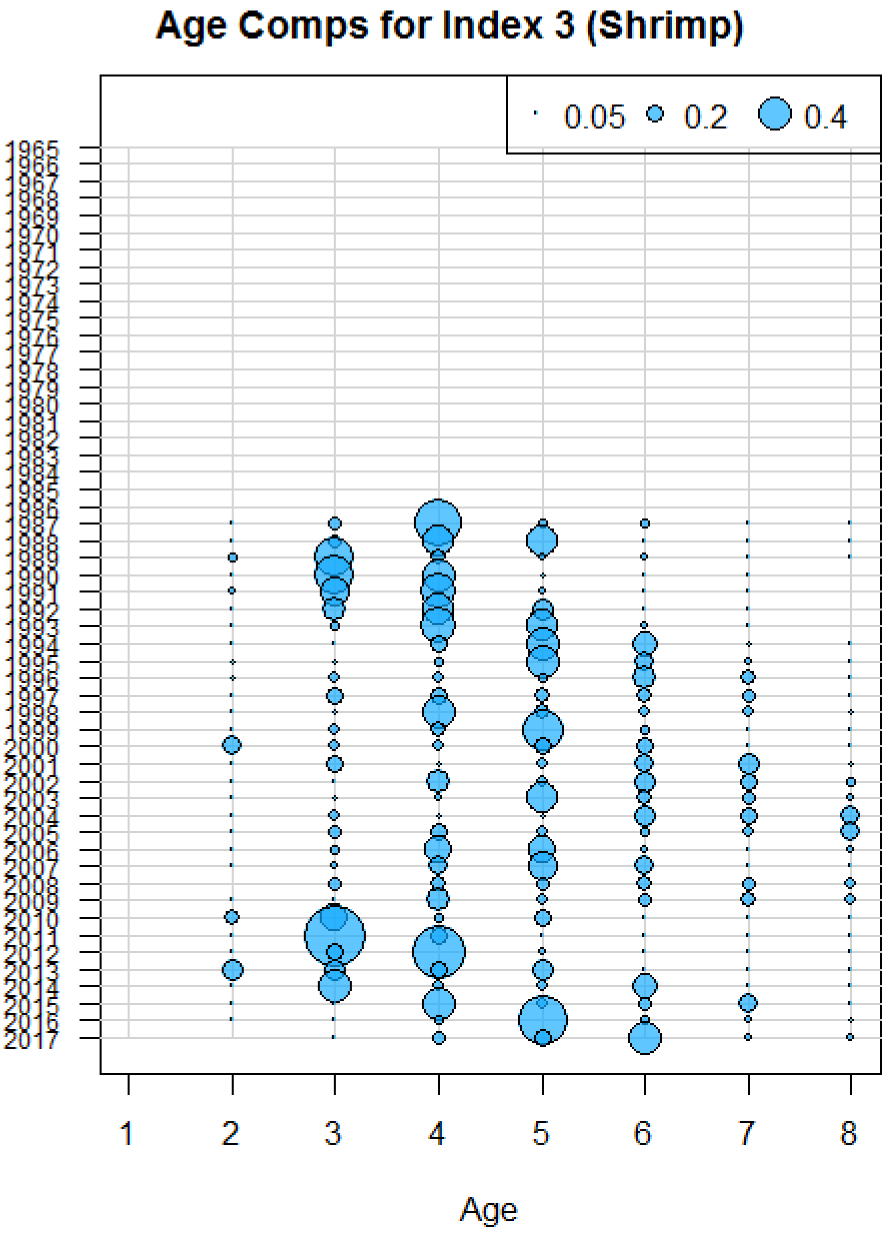


Figure B2- 9 Index of herring abundance derived from NEFSC stomach contents data +/- 2SD

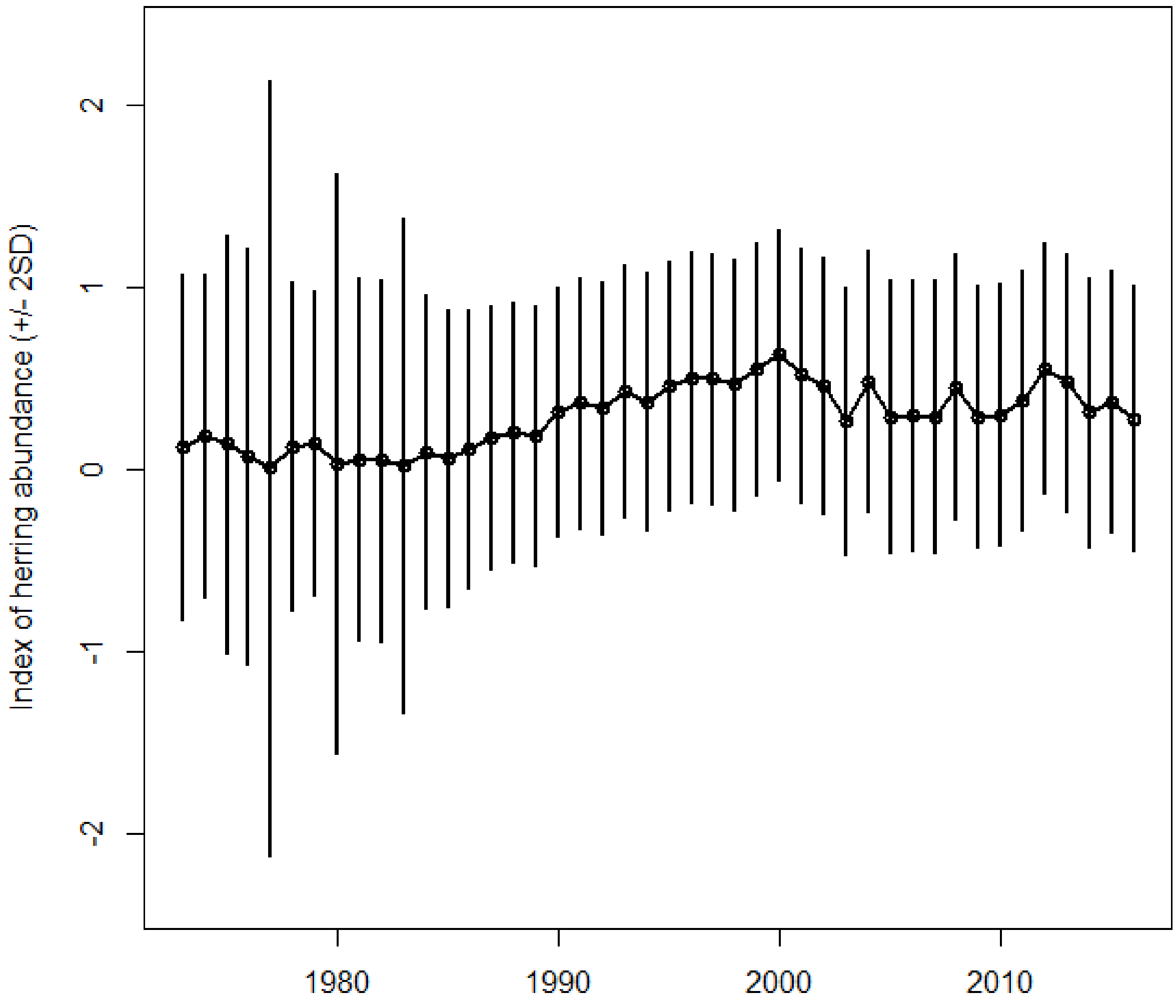


Figure B2- 10 Index of herring abundance derived from stomach contents data using data through 2014 (red) and with revisions to data during 2012-2014 and updated through 2016 (black)

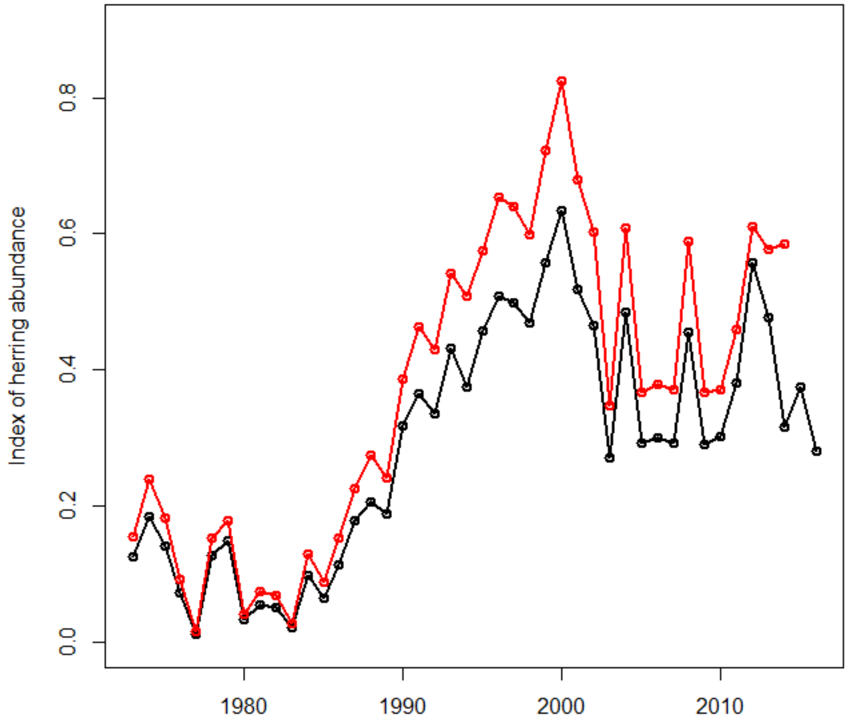
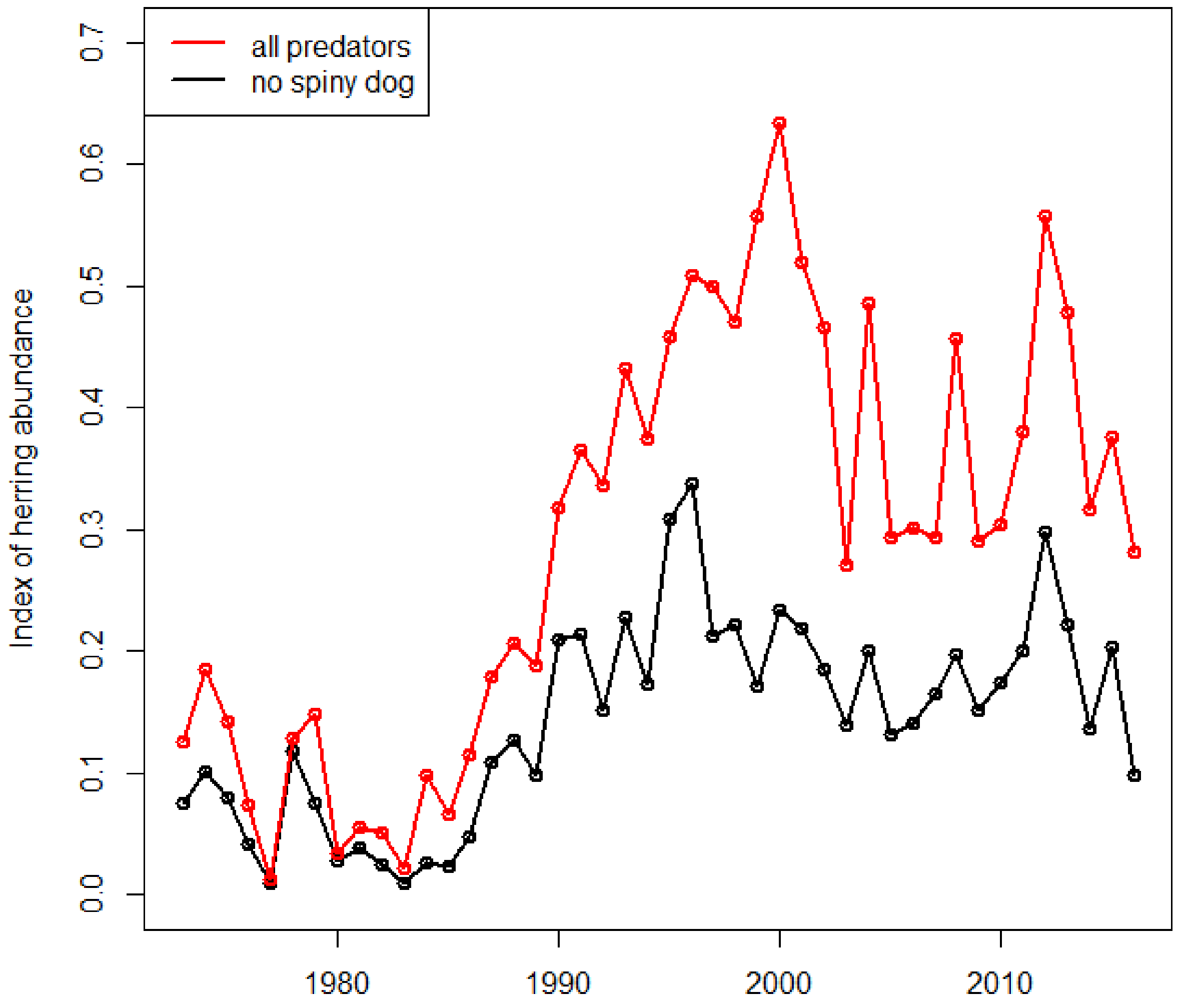
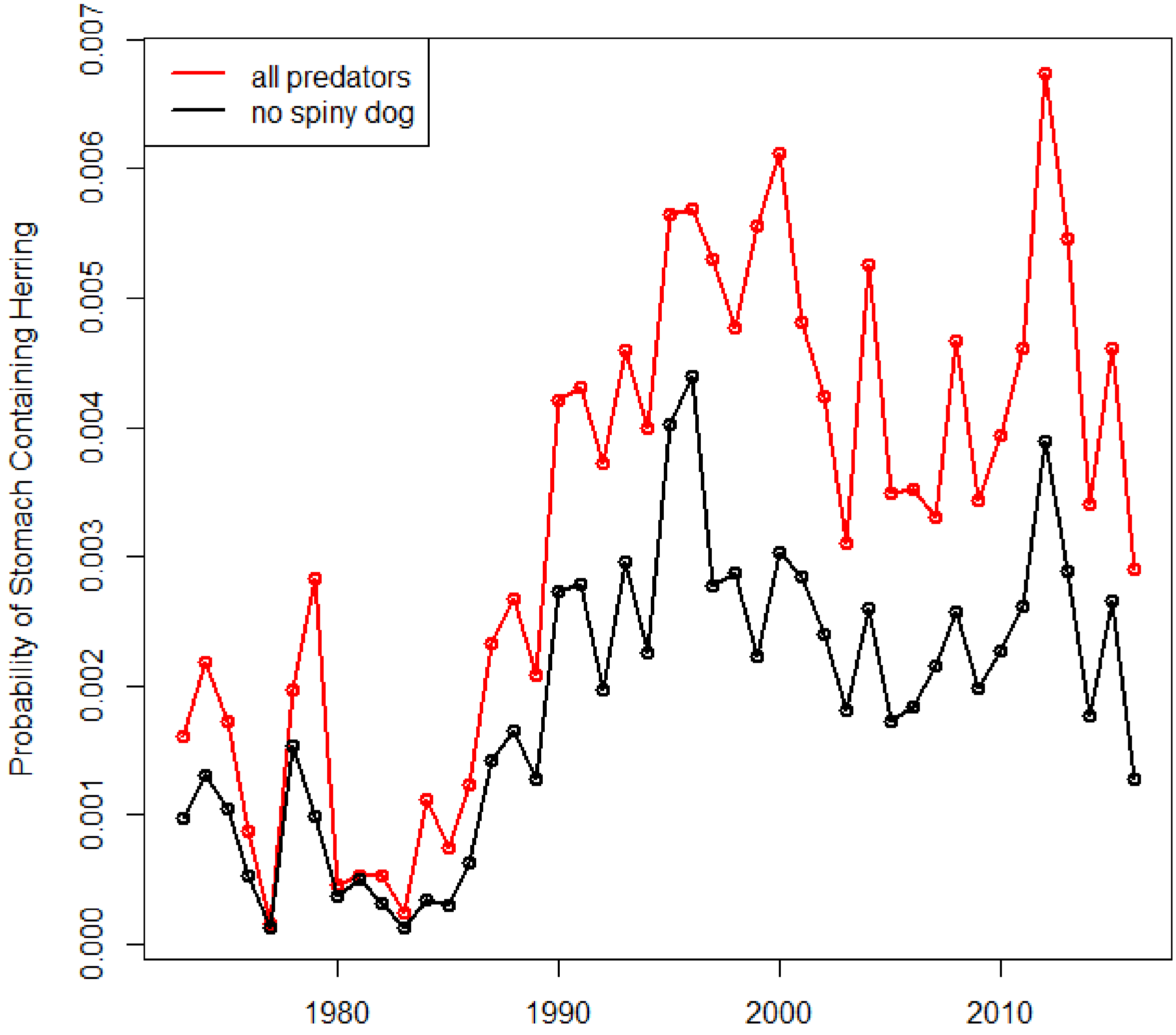


Figure B2- 11 Effect of removing spiny dogfish observations from the index of herring abundance derived from stomach contents data, and the effect on each element of the hurdle model used to create the index




all predators
no spiny dog
Probability of Stomach Containing Herring
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
1980
1990
2000
2010

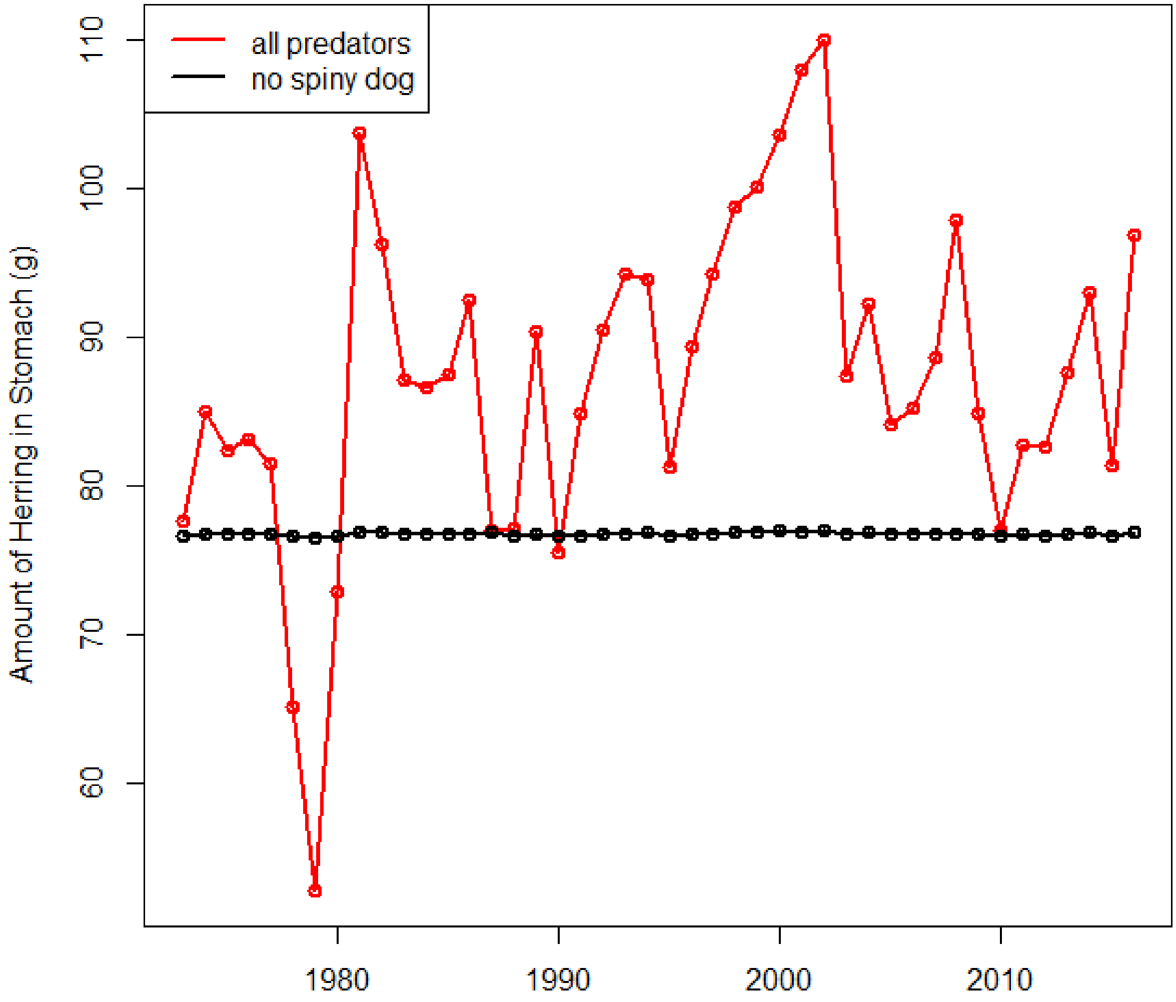

all predators
no spiny dog
Amount of Herring in Stomach (g)
60
70
80
90
100
110
1980
1990
2000
2010

Figure B2- 12 Relative retrospective pattern for the index of herring abundance derived from stomach contents data

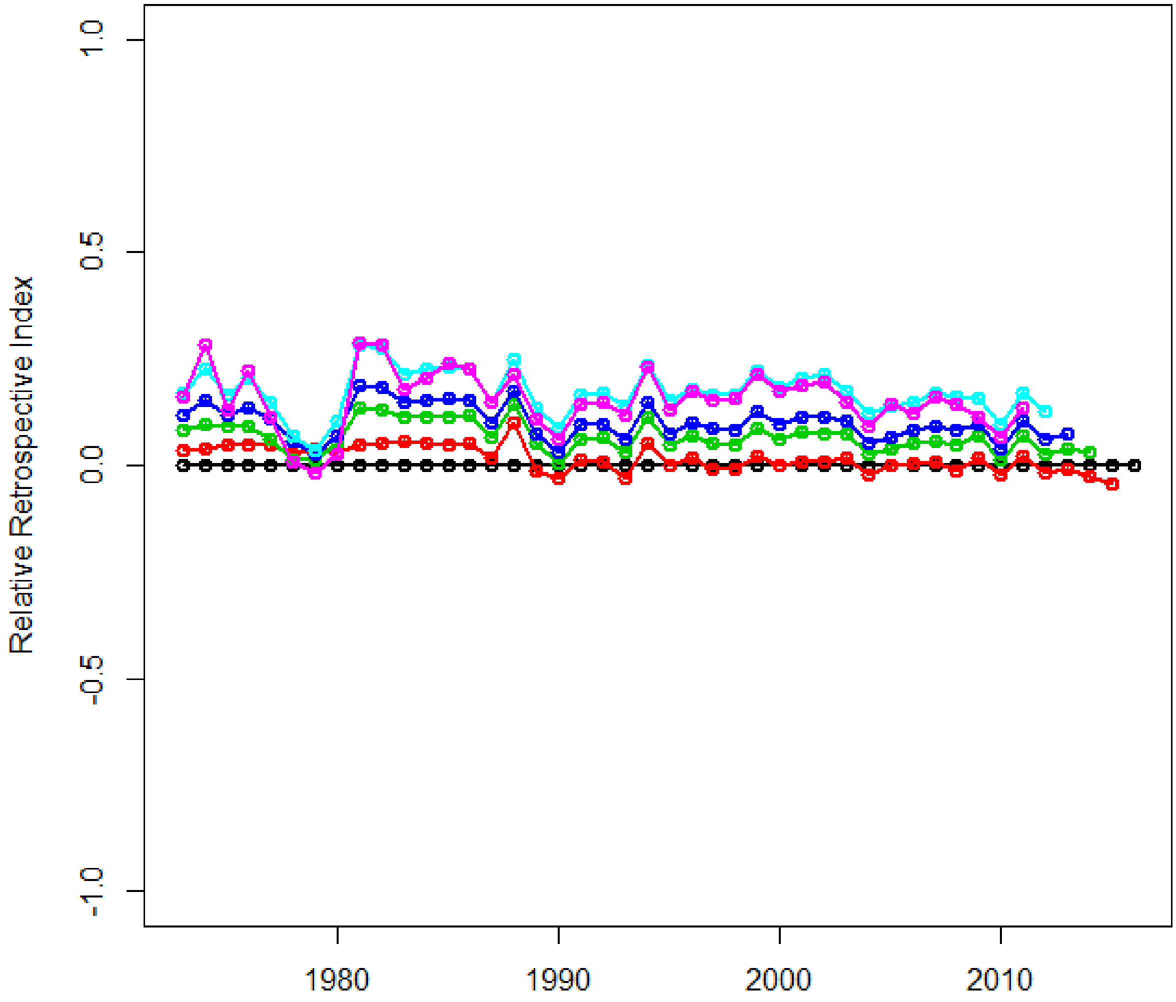


Figure B2- 13 Distribution of acoustic backscatter classified as Atlantic herring along the cruise track during the fall bottom trawl survey in 2016 on the HB Bigelow. Symbol size and color is related to areal acoustic backscatter, s_A (m^2 nmi^{-2}).

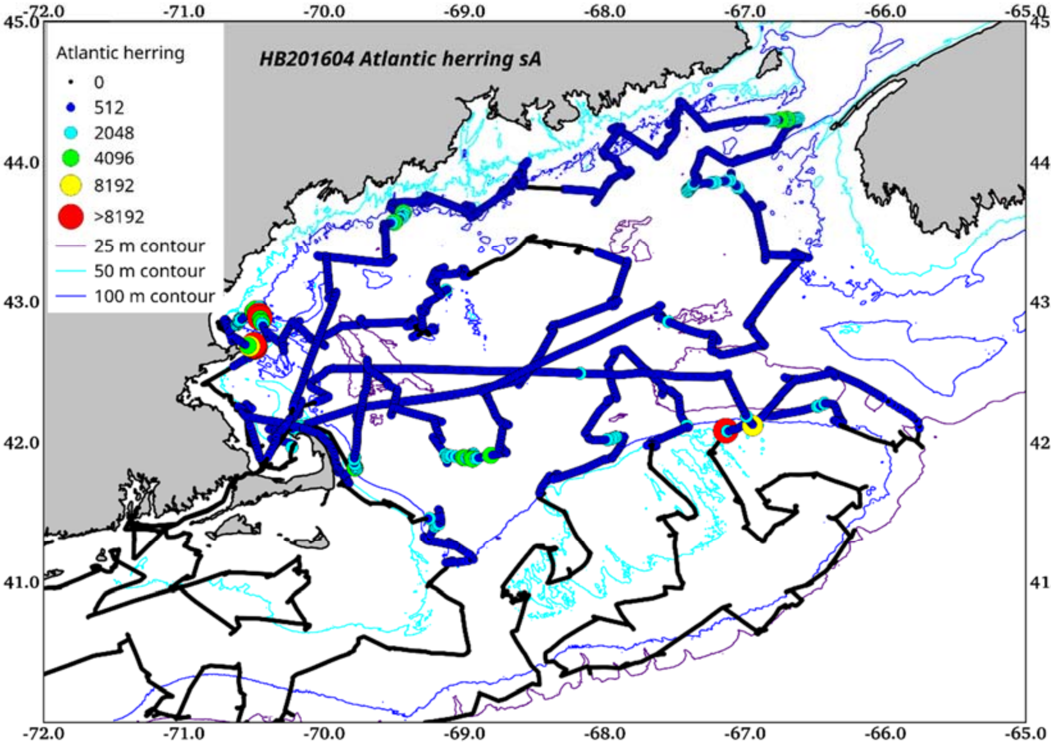
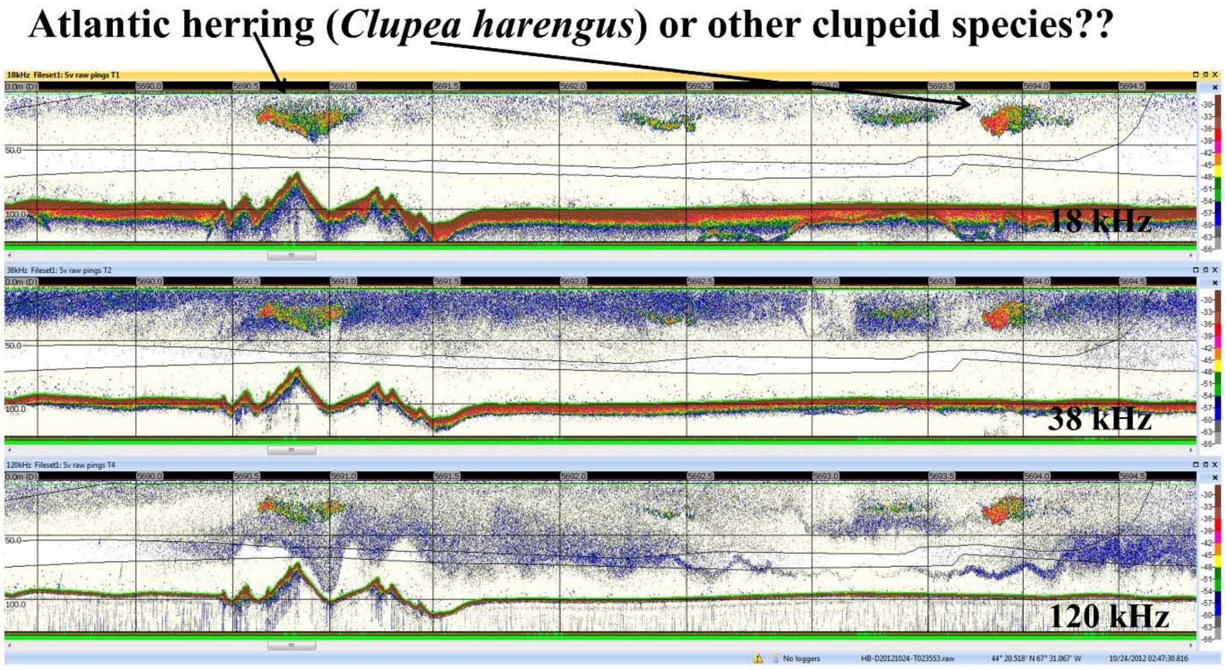


Figure B2- 14 Echogram of acoustic backscatter in the upper water column where the species composition can not be verified because the bottom trawl did not adequately sample these aggregations.



Atlantic herring (*Clupea harengus*) or other clupeid species??

Figure B2- 15 The finfish strata are shown in green. The “acoustic area” encompasses all strata where used to aggregate acoustic backscatter classified as Atlantic herring throughout the years from 1998-2017.

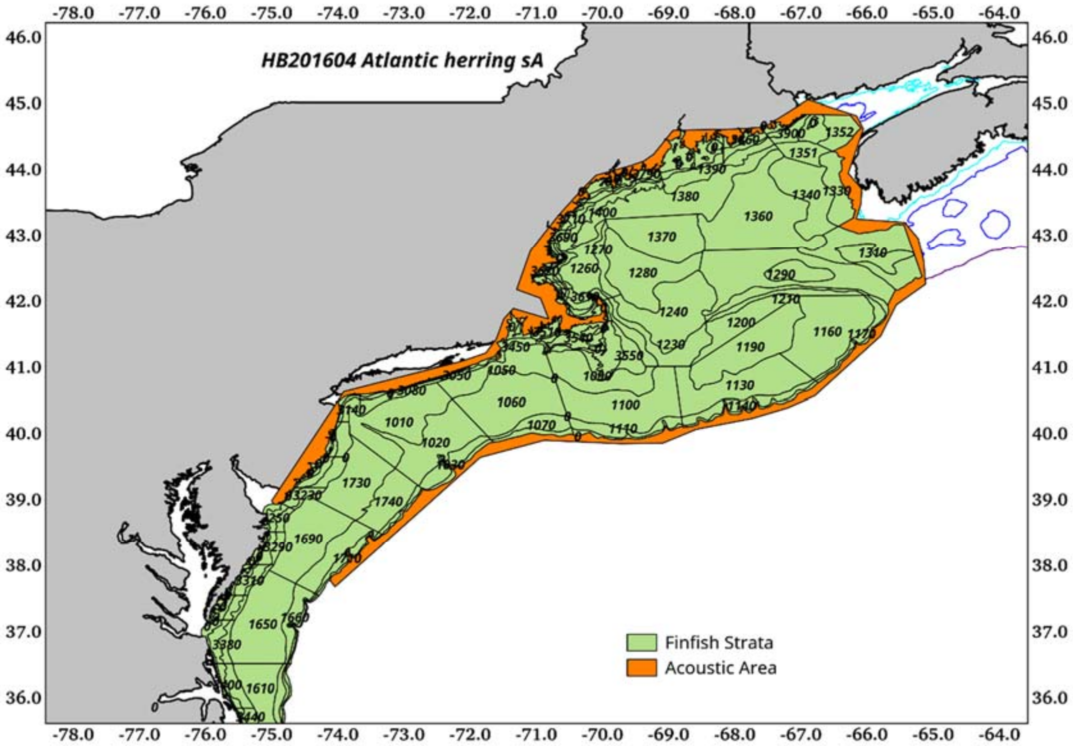


Figure B2- 16 Acoustic backscatter classified as Atlantic herring during the 2016 fall bottom trawl survey on the HB Bigelow overlaid on the finfish strata.

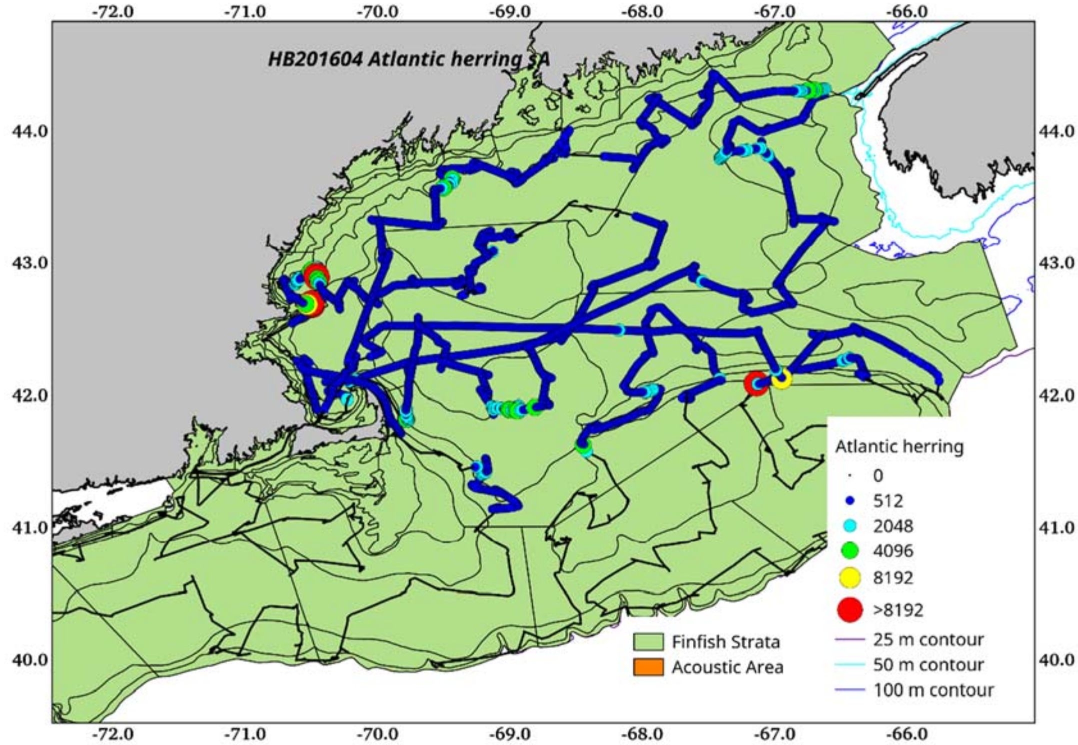
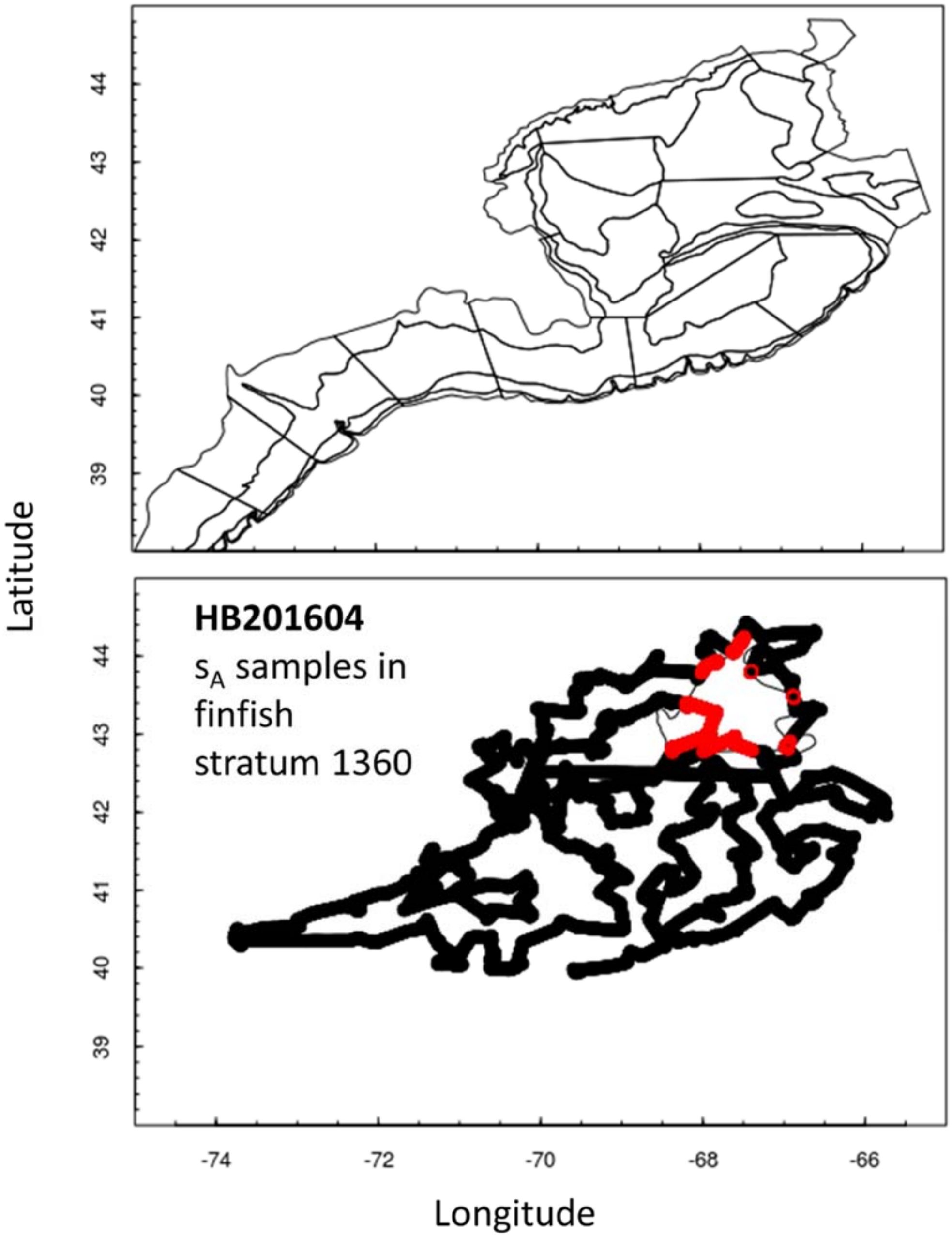


Figure B2- 17 The finfish strata included in the analyses (upper panel) and the entire set of sA samples (black symbols) and sA samples within stratum 1360 (red symbols) during the 2016 bottom trawl survey on the HB Bigelow



TOR B3: *Estimate consumption of herring, at various life stages. Characterize the uncertainty of the consumption estimates. Address whether herring distribution has been affected by environmental changes.*

Estimate consumption of herring, at various life stages. Characterize the uncertainty of the consumption estimates.

Summary

A time series of Atlantic herring consumption was estimated with an evacuation rate model for 12 fish predators of the NE US continental shelf, 1968-2016. Annual removal of herring amounted to 10s to 100s of thousands of MT by these predators.
Herring prey length data indicated adult herring (200+ mm) were primarily targeted, but this may be a result of limited inshore sampling coupled with sporadic inter-annual prey length sampling. Relative to January 1 biomass of herring available in the environment, an annual natural mortality proxy was produced using estimates of herring consumption. The time series average natural mortality was 0.12, reflecting predation of primarily adult herring by these predators.

Introduction

Fish food habits data from NEFSC bottom trawl surveys were evaluated for 12 herring predators (Table B3- 1). From these data, diet composition of herring, per capita consumption, and the amount of herring removed by the 12 predators were calculated. Combined with abundance estimates of these predators, herring consumption was summed across all predators as total herring consumption.

Methods

Every predator that contained Atlantic herring (*Clupea harengus*, and unidentified clupeid remains) was identified. From that original list, a subset of the top 12 predators comprising 94% of the occurrences of all herring predation and were regularly encountered by the sampling survey were included for estimating total herring consumption. Minimum sizes for herring predation were derived from the NEFSC Food Habits Database for each predator (Table B3- 1). Diet data were not restricted by geographic area and were evaluated over the entire northeast U.S. shelf as one geographic unit to match the assessed herring stock structure (see above).

Estimates were calculated on a seasonal basis (two 6 month periods) for each predator and summed per annum. Although food habits data collections for these predators started quantitatively in 1973 (Order Gadiformes only) and extends to the present (through 2016), not all herring predators were sampled during the full extent of this sampling program. Stomach sampling for the non-Gadiformes considered here began in 1977 and extends through 2016. For more details on the food habits sampling protocols and approaches, see Link and Almeida (2000) and Smith and Link (2010). This sampling program was part of the NEFSC bottom trawl survey program; further details of the survey program can be found in Azarovitz (1981), NEFC (1981), and Reid et al. (1999).

Basic Diet Data

Mean amounts of herring eaten ($D_{i,t}$; as observed from diet sampling) for each predator (i) and temporal scheme (t, fall or spring; year) were weighted by the number of fish at length per tow and the total number of fish per tow as part of a two-stage cluster design (See Link and Almeida 2000; Latour et al. 2007). These means included empty stomachs, and units for these estimates are in grams (g).

Numbers of Stomachs

The adequacy of stomach sample sizes were assessed with trophic diversity curves by estimating the mean cumulative Shannon-Wiener diversity of stomach contents plotted as a function of stomach number. The order of stomachs sampled was randomized 100 times, and cumulative diversity curves were constructed for each species focusing on the early 1980s when stomach sampling effort was generally lowest for the entire time series. The criteria for asymptotic diversity was met when the slope of the three proceeding mean cumulative values was ≤ 0.1 which was similar to previous fish trophic studies (e.g. Koen Alonso et al. 2002; Belleggia et al. 2008; Braccini 2008). A minimum sample size approximately equal to 20 stomachs for each predator per year-season emerged as the general cutoff for these asymptotes. Annual estimates of diet compositions of herring were estimated for each predator and season. For all predators, mean amounts of herring consumed ($D_{i,t}$) were not averaged between years with zero stomachs containing herring.

Consumption Rates

To estimate per capita consumption, the gastric evacuation rate method was used (Eggers 1977; Elliott and Persson 1978). There are several approaches for estimating consumption, but this approach was chosen as it was not overly simplistic (as compared to % body weight; Bajkov 1935) or overly complex (as compared to highly parameterized bioenergetics models; Kitchell et al. 1977). Additionally, there has been extensive use of these models (Durbin et al. 1983; Ursin et al 1985; Pennington 1985; Overholtz et al. 1999, 2000; Tsou and Collie 2001a, 2001b; Link and Garrison 2002; Link et al. 2002; Overholtz and Link 2007). Units are in g year^{-1}.

Using the evacuation rate model to calculate consumption requires two variables and two parameters. The daily per capita consumption rate of herring, $C_{i,t}$ is calculated as:

$$C_{i,t} = 24 \cdot E_{i,t} \cdot D_{i,t} \qquad ,$$

where 24 is the number of hours in a day. The evacuation rate $E_{i,t}$ is:

$$E_{i,t} = \alpha e^{\beta T_{i,t}} \qquad ,$$

and is formulated such that estimates of mean herring eaten ($D_{i,t}$) and ambient temperature ($T_{i,t}$) as stratified mean bottom temperature associated with the presence of each predator from the NEFSC bottom trawl surveys (Taylor and Bascuñán 2000; Taylor et al. 2005) are the only data required. The parameters α and β were set as 0.002 and 0.115 for the elasmobranch predators respectively and 0.004 and 0.115 for the teleost predators respectively (Tsou and Collie 2001a, 2001b, Overholtz et al. 1999, 2000).

To evaluate the performance of the evacuation rate method for calculating consumption, a simple sensitivity analysis had been previously executed (NEFSC 2007). The ranges of α and β within those reported for the literature do not appreciably impact consumption estimates (< half an order of magnitude), nor do ranges of *T* which were well within observed values (<< quarter an order of magnitude). An order of magnitude change in the amount of food eaten linearly results in an order of magnitude change in per capita consumption. Variance about any particular species of predator stomach contents has a CV of ~50%. Estimates of abundance, and changes in estimates thereof, are likely going to dominate the scaling of total consumption by a broader range of magnitudes than the parameters and variables requisite for an evacuation method of estimating consumption.

Fish Predator Abundance Estimation

The scaling of total consumption requires information on predator population abundance of sizes actively preying on herring (Table B3- 1). Where age information was available, minimum size was converted to age using the average age at length from Table B3- 1. Abundance estimates were either from assessment models or swept area abundance for each predator (Table B3- 2). Predators with a short time series (data not available 1968 -2016) were extrapolated back using survey indices and their relationship with abundance estimates (Atlantic cod, pollock, summer flounder, and goosefish) or landings using the relationship between landings and abundance (bluefish). Species estimated using swept area abundance (winter and thorny skate, silver and red hake, and sea raven) used an assumed q= 1.0. For Georges Bank cod and goosefish, the most recent assessment model (cod) was not accepted (NEFSC 2015) or ageing method invalidated (goosefish; Richards 2016); thus, abundance data from previously accepted assessments were used and the time series expanded based on the relationship with survey indices.

Scaling Consumption

Following the estimation of consumption rates for each predator and temporal (t) scheme they were scaled up to a seasonal estimate ($C'_{i,t}$) by multiplying the number of days in each half year:

$$C'_{i,t} = C_{i,t} \cdot 182.5 \quad .$$

These were then summed to provide an annual estimate, $C'_{i,\,year}$:

$$C'_{i,year} = C_{i,fall} + C_{i,spring} \quad .$$

and were then scaled by the annual abundance to estimate a total annual amount of herring removed by predator, $C_{i,\,year}$:

$$C_{i,year} = C'_{i,year} \cdot N_{i,year} \qquad .$$

To complement the herring assessment time series prior to 1973, 5-yr averages of annual per capita consumption of herring ($C'_{i,\,year}$) for the gadiform predators (1973-1977) and non-gadiform predators (1977-1981) were estimated and scaled for each predator by the available abundance data from 1968-1976. The final herring consumption time series was 1968-2016. The total amount of herring removed ($C_{i,\,year}$) were then summed across all *i* predators to estimate a total amount of herring removed, C_{year}:

$$C_{year} = \textstyle\sum_i C_{i,year} \qquad .$$

The total consumption of herring per predator and total amount of herring removed by all predators are presented as thousands of metric tons year^{-1}.

Prey Lengths of Herring

Prey length data were available for herring consumed by the 12 fish predators considered here. In total, 2,916 length records were collected from 1973-2016. Not all observed herring prey had length data available due to digestion or other sampling constraints; thus, sampling was sporadic year to year. The data were aggregated by decade and kernel density plots produced for each season.

Results and Conclusions

Total consumption of herring by fish predators was variable throughout 1968-2016 with the amount of herring removed equal to 32 MT year^{-1} (minimum) and 390,233 MT year^{-1} (maximum; Figure B3- 1). Years with lesser total amounts of herring predation were earlier in the time series (1968-1987; averaging 61,924 MT year^{-1} compared to later in the time series (1987-2016; averaging 137,051 MT year^{-1}).

Prey length data revealed much of the predation from fishes collected on the bottom trawl survey center on herring around 200 mm or greater for the fall and spring by decade (Figure B3-2). We suspect some of this is due to the bottom trawl survey design focusing on offshore waters and sporadic sampling of prey-lengths per year. It is believed similar or even greater amounts of predation on juvenile herring is likely occurring on this shelf primarily inshore, and in addition to fish predators, by other predators such as birds or marine mammals.

As a proxy for natural mortality due to predation, the proportion of total herring consumption to January 1 biomass of herring from the most recent herring benchmark assessment (NEFSC 2012) was estimated (Figure B3- 3). Here, predation by the 12 predators accounted for approximate proportions of 0.0002 (minimum) and 0.64 (maximum) of the population from 1968-2011. The time series mean of this proxy equaled 0.12. Considering that these estimates largely reflect predation on adult herring, additional work assessing consumption of herring less than 200 mm is warranted, particularly for the inshore waters of this shelf.

Address whether herring distribution has been affected by environmental changes.

Herring distribution at the shelfwide scale has been fairly stable from the 1970's to the present (based on observations from the NEFSC bottom trawl survey). This is in contrast to many New England species, which show significant along-shelf (northeastward) trends in their centers of distribution (see https://www.nefsc.noaa.gov/ecosys/current-conditions/species-dist.html). However, there is evidence that herring are found in deeper survey strata in recent years.

We compared NEFSC trawl survey information to determine whether herring distribution has changed. Comparisons of spring and fall kernel density maps from the 1970's (blue) and the most recent years (red, 2014-2017) shows no substantial change in herring distribution (Figure B3- 4). Further, a time series of the mean along shelf distance from both spring and fall surveys shows no trend over time, indicating that the center of the herring population has remained the same (Figure B3- 5). However, there is a significant long term trend in the mean depth of stations where herring are caught on the survey (Figure B3- 5), which may reflect less herring biomass over shallower Georges Bank and more over deeper Gulf of Maine now than in the past (supported by the kernel density maps).

Atlantic herring’s overall climate vulnerability ranking was low in a recent assessment applied to many Northeast U.S. shelf species (Hare et al. 2016). Climate exposure of all Northeast U.S. species including herring was considered high, but Atlantic herring had low biological sensitivity. While the assessment ranked Atlantic herring as having a high potential for distribution shifts due to their low habitat specialization, highly mobile adult stage, and long larval duration with potentially broad dispersal, observations from the NEFSC surveys indicate that a shift has not yet happened.

Table B3- 1 Top 12 predators of Atlantic herring (*Clupea harengus* and unidentified clupeid remains) along with minimum sizes for herring predation from the NEFSC Food Habits Database and average age (where available).

Common Name	Scientific Name	Minimum Size (cm)	Avg. Age (years)
Spiny dogfish	*Squalus acanthias*	29	
Winter skate	*Leucoraja ocellata*	39	
Thorny skate	*Amblyraja radiata*	41	
Silver hake	*Merluccius bilinearis*	13	0.8
Atlantic cod	*Gadus morhua*	16	1.1
Pollock	*Pollachius virens*	19	1.4
White hake	*Urophycis tenuis*	21	0.4
Red hake	*Urophycis chuss*	24	1.3
Summer flounder	*Paralichthys dentatus*	23	0.9
Bluefish	*Pomatomus saltatrix*	17	0.0
Sea raven	*Hemitripterus americanus*	13	
Goosefish	*Lophius americanus*	12	1.2

Table B3- 2 Summary of methods used for determining predator abundances.

Common Name	Method
Spiny dogfish	Model-based estimate
Winter skate	Swept area biomass, fall offshore
Thorny skate	Swept area biomass, fall offshore
Silver hake	Swept area biomass, fall offshore
Atlantic cod	ASAP model, two stocks combined, linear extrapolation GB data from previously accepted model used
Pollock	ASAP model and ln curve extrapolation
White hake	Model-based estimate with fall q 2012-13 (last benchmark)
Red hake	Swept area biomass, fall offshore
Summer flounder	ASAP model and ln curve extrapolation
Bluefish	ASAP model and linear extrapolation
Sea raven	Swept area biomass, fall offshore
Goosefish	SCALE model and linear extrapolation Ageing method invalidated in 2015, but data from previously accepted model used

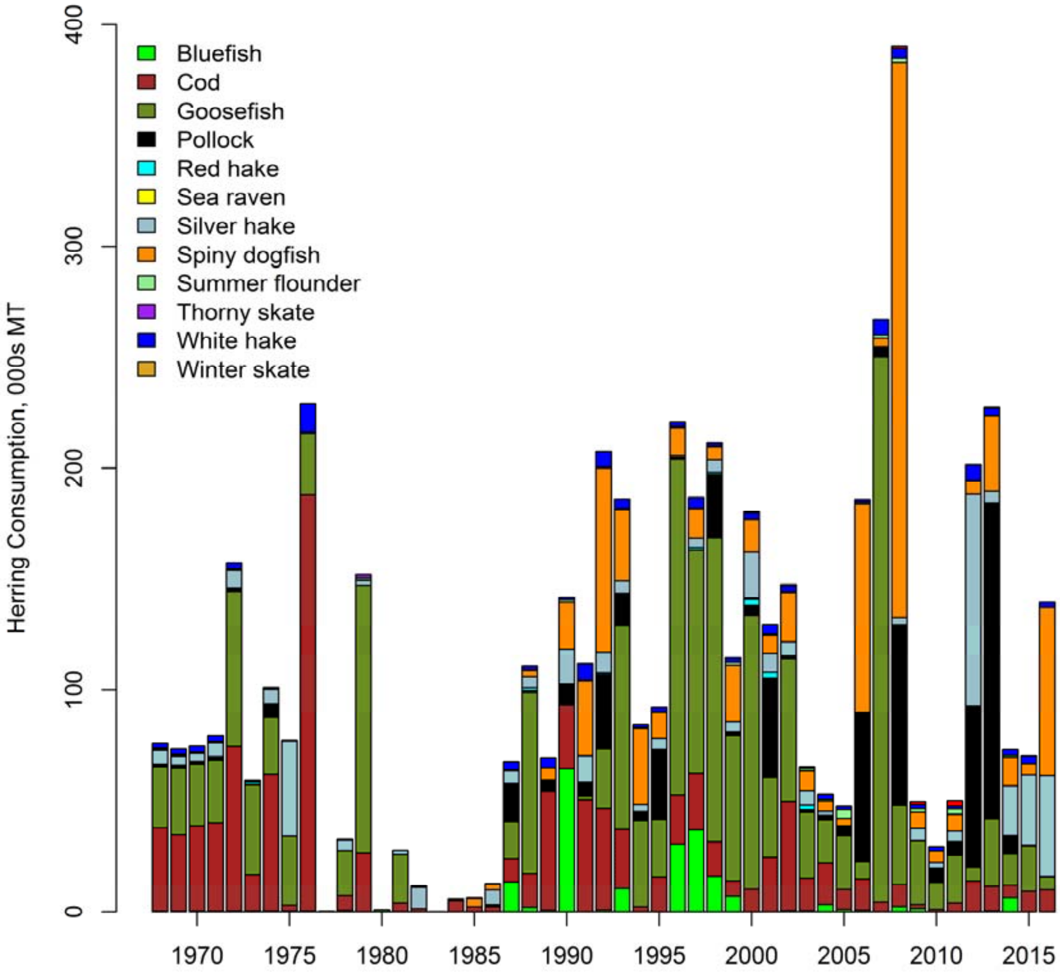


Figure B3- 1 Time series of herring consumption (000s MT) by 12 fish predators.

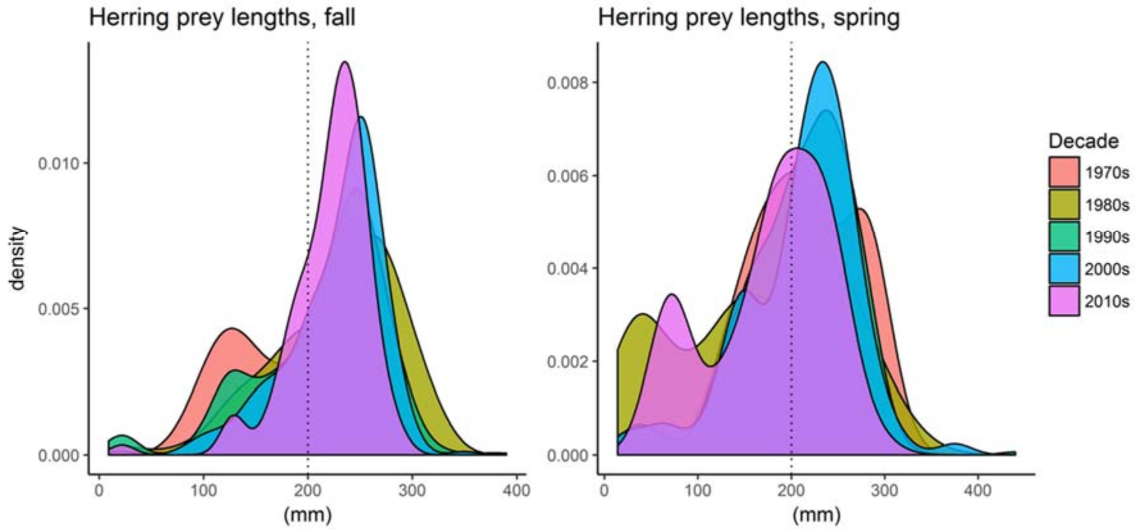


Figure B3- 2 Gaussian kernel density plots of herring prey lengths by decade for the spring and fall, 1973-2016.

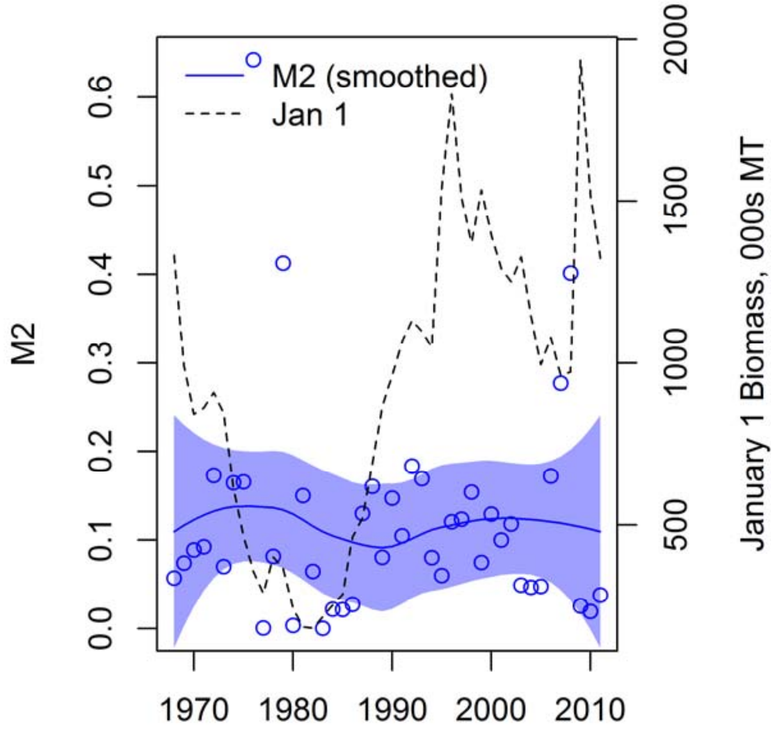


Figure B3- 3 Proxy estimate of natural mortality due to predation (M2) and January 1 biomass of herring, 1968-2011. M2 smoother is loess with span = 0.8 and 95% ci.

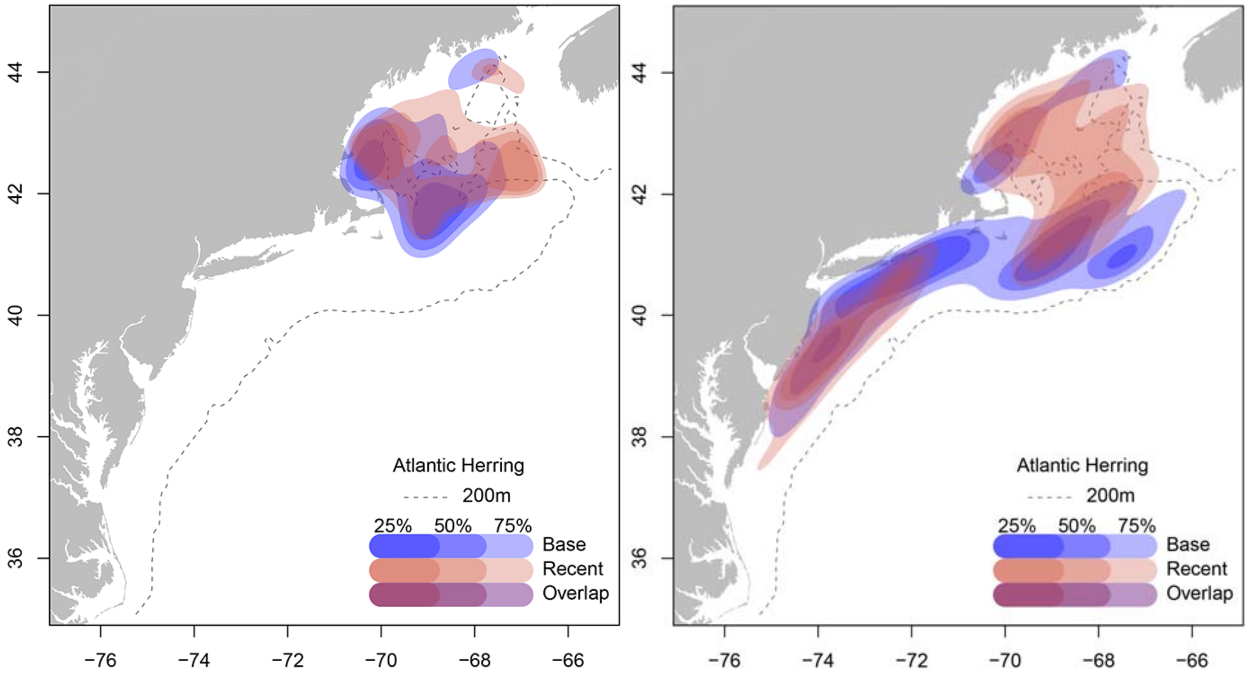


Figure B3- 4 Atlantic herring historical (1970s; blue) and current (2014-2017; red) distribution in the fall (left) and spring (right)

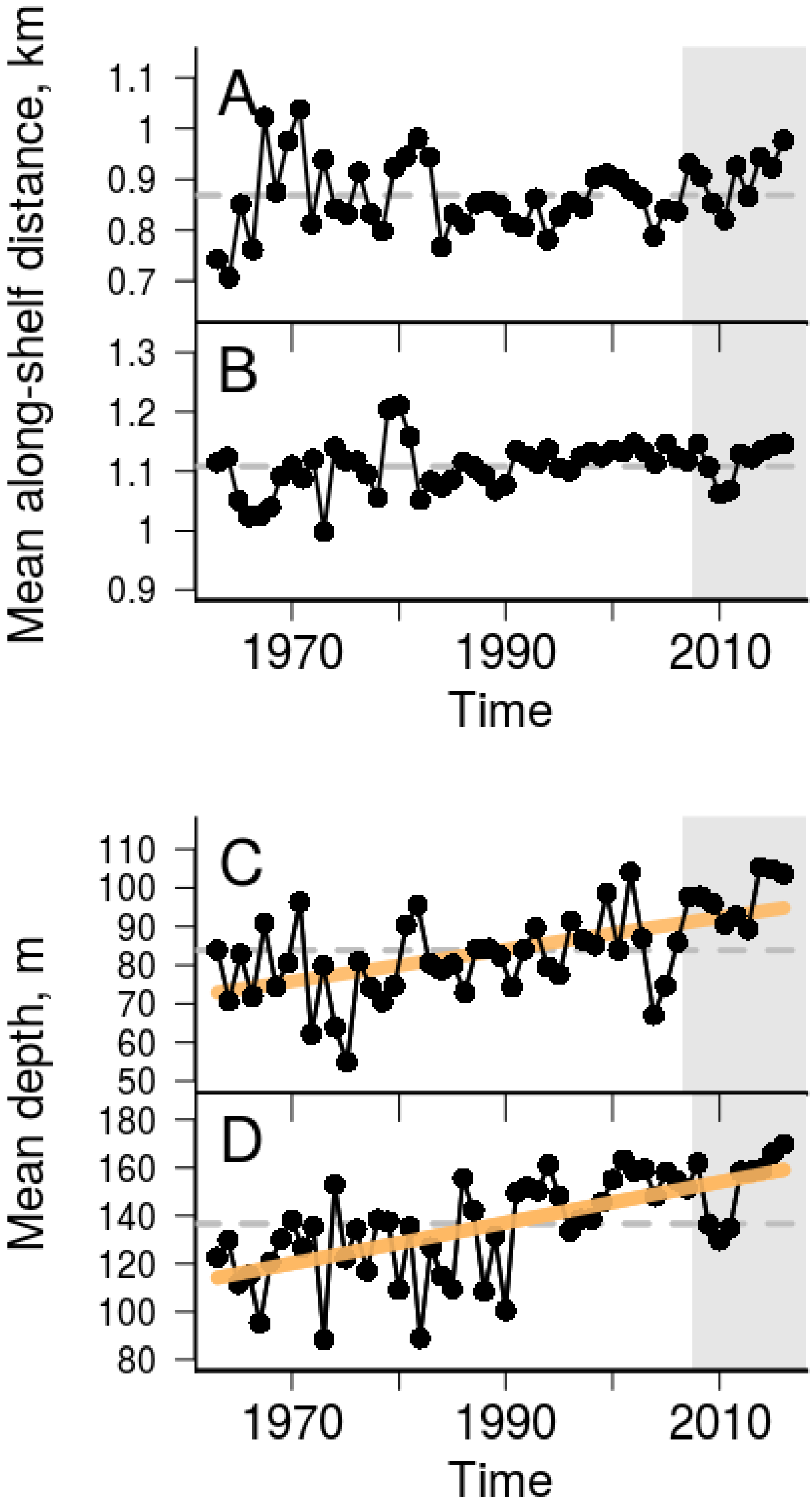


Figure B3- 5 Atlantic herring distribution trends (Along shelf distance in A. Spring, B. Fall, and mean depth in C. Spring, D. Fall)

TOR B4: *Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and estimate their uncertainty. Incorporate ecosystem information from TOR B3 into the assessment model, as appropriate. Include retrospective analyses (both historical and within-model) to allow a comparison with previous assessment results and projections, and to examine model fit.*

Update the 2015 ASAP model

The ASAP model formulation (Age Structured Assessment Program, Legault and Restrepo 1998) used in the 2012 (NEFSC 2012) and 2015 (Deroba 2015) stock assessments was updated using data through 2017. A brief description of this model formulation is provided here. The models used two fleets (mobile and fixed) as described above (see TOR B1). Indices of abundance included spring, fall, and summer NMFS bottom trawl surveys. The indices of abundance collected with the Biglow from 2009 to the terminal year of each assessment were calibrated to Albatross IV equivalent catches. Natural mortality was based on a combination of the Hoenig and Lorenzen methods, with the Hoenig method providing the scale of natural mortality and the Lorenzen method defining how natural mortality declined with age (Hoenig 1983; Lorenzen 1996; Brodziak et al. 2011). The natural mortality rates during 1996 to the terminal year of each assessment were increased by 50% from these base rates. In 2012, predatory consumption estimates of Atlantic herring were used in justifying time varying M (i.e., the 50% increase from base rates) that also resolved a retrospective pattern (NEFSC 2012). In the 2015 operational assessment, however, a retrospective pattern re-emerged and predatory consumption estimates no longer supported the time varying M (Deroba 2015). Reconsideration of time varying M is not permissible in an operational assessment, and so this feature was retained in the model, but an adjustment for the retrospective pattern was made for determining stock status and in short-term projections that informed catch specifications. In updating this model formulation through 2017, all model specifications (e.g., selectivity, data weighting, likelihood penalties) were identical to the previous assessments (NEFSC 2012; Deroba 2015), with the exception of a correction to input data. In the course of this assessment, the Working Group discovered that the age 8+ fall NMFS bottom trawl survey data were incorrectly calculated as an age 7+ value. This error was corrected.

Fits to catch, survey trends, and age compositions in the form of residual diagnostics were generally similar between the updated model and the 2015 assessment (results not shown). The updated model also exhibited a retrospective pattern, similar in severity to that of the 2015 assessment (Figure B4- 1).

A comparison of time series trends between the updated model and the 2015 assessment (with the plus group corrected in both models) showed a decrease in scale in the updated model, with the retrospectively adjusted SSB value from the 2015 assessment being similar to the estimate from the updated model (Figure B4- 2).

Review of models considered for this assessment

Three modeling platforms with different data inputs and different model structures were considered to varying degrees during this assessment. Building from previous assessments, the Working Group spent the most time evaluating the ASAP model, which ultimately was used for the base assessment (Legault and Restrepo 1998). A state-space assessment model (SAM; Nielsen and Berg 2014) was also developed. The Working Group was not as familiar with the SAM model as ASAP, and so SAM was ultimately used a point of comparison for ASAP fits. The details of the SAM configuration are in Appendix B2. An attempt was also made at model averaging the ASAP and SAM models (Appendix B3). Largely in response to research recommendations from previous assessments, a Stock Synthesis (SS) model was briefly reviewed (Methot and Wetzel 2013). The research recommendations that the SS model was primarily intended to address were the ability to fit to length composition data (ASAP and SAM cannot) and consideration of stock structure. So, a two area SS model was developed that fit to a broad range of data types, including length and conditional age-at-length composition data. The SS model reviewed by the Working Group during the Model Meeting, May2-4, 2018, had unresolved residual patterns in the composition data. Furthermore, in order to consider the estimation of movement among areas, the SS model assumed that 100% of Atlantic herring from each spatial area returned to their natal location to spawn. The Working Group felt that this assumption was unjustified and likely invalid. Given these concerns, the Working Group did not consider the SS model viable at this time. The Working Group agreed that the consideration of stock structure in the herring assessment may not be reasonable until more information is available on movement rates and the relative size of each sub-stock, which might come from morphometrics, tagging, or some other source. The Working Group recommended the continued consideration of using length composition data, whether through SS or some other model platform. The details of the SS model are in Appendix B4.

Base ASAP model development

The base ASAP model made structural changes to the previous assessment (e.g., M, selectivity), included new index time series, and re-evaluated some other relatively minor issues (e.g., weak likelihood penalties). The reasoning behind some of these modeling choices was described below. Some consequences of the changes to model structure and data inputs were documented in more detail in the *Sensitivities to the base ASAP model* section below.

The base model considered age 1 to an age 8 plus group and covered the time period 1965-2017. The age 8 plus group was based on the difficulties that ASAP had estimating the abundance of age 9 and older herring in the first year (i.e., 1965) and concerns about the reliability of age data for older ages in previous assessments (NEFSC 2012). The model was started in 1965 when catch data from all sources (i.e., US and Canadian weir) was first available.

Estimates of abundance at age in the first year (i.e., 1965) in previous assessments were imprecisely estimated and sometimes caused issues of model non-convergence (NEFSC 2012). To reduce imprecision and help with convergence, these estimates were previously given a relatively weak likelihood penalty for deviating from initial starting guesses. This penalty was removed in the base model, and initial abundances at age were estimated as deviations from an equilibrium age structure (Legault and Restrepo 1998). While these initial abundance estimates were still relatively imprecise (CVs ranging from 0.37-3.09), the imprecision was not considered problematic and the model consistently converged. A model with no likelihood penalty was also considered more parsimonious.

The base ASAP model used age- and time- invariant M = 0.35, which was a value based on the longevity methods of Hoenig (1983). The method assumed a maximum age equal to 14, which was the oldest age ever observed in commercial or survey gear catches and was consistent with maximum ages reported elsewhere (Collette and Klein-MacPhee 2002). Implied amounts of mortality based on the constant M were generally higher or similar to estimates of predatory consumption from stomach contents data (Figure B4- 3). The estimates of predatory consumption from stomach contents are likely underestimates, and so the Working Group was comfortable with implied amounts of mortality from the assessment being higher. The estimates of predatory consumption from stomach contents are also highly imprecise (although largely unquantified), and so the Working Group was satisfied with the general similarity of this comparison, and felt considering changes to M based on this comparison to be unjustified. This constant M was a departure from previous assessments that included age- and time-varying M (NEFSC 2012; Deroba 2015). The 50% increase in M beginning in 1996 was no longer justified given that that this increase in M no longer resolved retrospective patterns in the previous operational assessment (Deroba 2015) and was not needed to create general agreement between estimates of predatory consumption from stomach contents data and the amount of herring implied by the input M. Time-invariant M was also generally supported by a predation pressure index of M (Richards and Jacobson 2016; Appendix B5). The age-variant M based on a combination of the Hoenig and Lorenzen methods (Hoenig 1983; Lorenzen 1996; Brodziak et al 2011) provided a nearly identical fit to using a constant M (Neg. LL = 3773 for constant M and 3774 for age-variant), and so the Working Group agreed to use the more parsimonious constant M. A likelihood profile over time- and age-invariant M values found a minimum at 0.45 (Figure B4- 4).

For the mobile gear fishery, selectivity at age was freely estimated for ages 1-6, while selectivity at ages 7-8 was fixed at 1.0. Preliminary assessment fits were attempted that also estimated selectivity at ages 7 and 8, but estimates were at or near 1.0. The working group agreed that the mobile gear fishery, which is characterized by mostly large scale trawlers and purse seine operations, should have a flat-topped selectivity curve. Previous assessments (NEFSC 2012; Deroba 2015) also fixed the selectivity at ages 5 and 6 to 1.0. Estimating selectivity for these ages, however, improved model fit (Neg. LL improved by 7 units) and reduced some age composition residual patterns (Figure B4- 5).

The fixed gear fishery almost exclusively harvests age 2 fish, while other ages are caught in relatively small proportions (see TOR B1). Consequently, selectivity at age 2 was fixed at 1.0, while selectivity for all other ages was estimated. Previous assessments (NEFSC 2012; Deroba 2015) included a relatively weak likelihood penalty for deviations from initial guesses for each estimated selectivity at age parameter. These penalties were to help with precision and convergence, but were unnecessary for the base model here and so eliminated.

Selectivity at age on the NMFS spring survey during 1968-1984 was fixed and equaled 0.0 at ages 1 and 2, 0.5 at age 3, and 1.0 at ages 4-8. Selectivity-at-age on the NMFS fall survey during 1965-1984 was fixed and equaled 0.0 at ages 1-3, 0.5 at age 4, and 1.0 at ages 5-8. The selectivities for these surveys were fixed because no age composition data was available. The values input for the selectivities were justified in previous assessments by examining length compositions for each survey (see TOR B2). Sensitivity runs excluding these two surveys suggest that the base model is robust to their inclusion/exclusion and selectivity pattern, but that they provide some information for the estimation of initial abundance at age (Figure B4- 6), and so the Working Group agreed that they should be retained.

The NMFS spring survey during 1985-2017 (Albatross and Bigelow vessels) rarely caught any age 1 herring, while the fall frequently caught low proportions of age 1 herring (see TOR B2). In some years, however, a relatively large proportion of age 1 herring were caught.Previous assessments (NEFSC 2012) have found that assessment models would "chase" these signals about year class strength and estimate a relatively high recruitment in those years with high age 1 catches, which created retrospective patterns as more years of data about the given year class revealed a much weaker signal As in previous assessments, this Working Group agreed that the age-1 catches from these surveys were driven more by measurement uncertainty than by true measures of cohort strength. Consequently, age 1 catches from these surveys were discarded from the base ASAP model and selectivity at age 1 fixed to 0.0. For the NMFS spring survey during 1985-2008 (Albatross) and 2009-2017 (Bigelow), selectivity-at-age was freely estimated for ages 2-3 and was fixed and equaled 1.0 for ages 5-8. Age 4 selectivity was initially estimated, but kept hitting the bound of 1.0, which can cause convergence problems, and so this age was fixed at 1.0. For the NMFS fall survey during 1985-2008 (Albatross) and 2009-2017 (Bigelow), selectivity was logistic. Using age based selectivity in the spring resolved age composition residual patterns that were not present in the fall survey, making the more flexible age based alternative unnecessary in the fall (NEFSC 2012). As the NMFS summer survey used an average of the spring and fall NMFS survey age length keys, selectivity at age 1 was also assumed 0.0 in this survey. Otherwise, selectivity followed a logistic pattern.

No age composition data is available to inform selectivity estimation for the acoustic survey (as collected during the fall bottom trawl survey; see TOR B2). While all ages should theoretically be detected by the acoustic survey, some younger ages may be unavailable to the survey if they are not present at the time of sampling, which may be especially true during the fall when spawning occurs. A model with knife-edged selectivity at age 3, informed by the maturity data, provided a better fit than a model with full selection at all ages (Neg. LL better by

7 units). Consequently, the base model assumed knife-edged selectivity at age 3 for the acoustic index.

Input annual effective sample sizes (ESS) for the mobile and fixed gear fishery age composition data were initially set equal to the number of trips sampled for age in each year for each fishery, with a minimum of 5 and maximum of 150. In years for which no age samples were taken from the US fixed gear fishery and the age composition for the fleet relied solely on Canadian data, the ESS was set equal to 5 (the number of Canadian samples was unavailable; NEFSC 2012). Survey input annual ESS were initially set equal to the number of positive survey stations (i.e., stations that captured at least one herring) for each year and survey. All of these ESS were then iteratively reweighted as described for the multinomial distribution in Francis (2011).

The CVs on each survey data point were initially set equal to the CV estimated for a given survey in each year (see TOR B2). These CVs were then adjusted in an iterative fashion until the root mean square error (RMSE) of the standardized residuals for each survey was approximately within the 95% confidence intervals of the RMSE expected at the given sample size (i.e., number of years) for each survey (Figure B4- 7; Table B4- 1). The RMSE in this context was used as a measure of the consistency between the input precision of the survey values (i.e., CVs) and the uncertainty in the fits to a given survey index (i.e., variance of the standardized residuals). An RMSE equal to 1.0 suggests that the input CVs exactly match the uncertainty in the model fit. An RMSE greater than 1.0 suggests that the CVs need to be increased and the opposite for an RMSE less than 1.0. In this assessment, when the RMSE was outside of the 95% confidence intervals of the RMSE expected at the given sample size for a survey, each input CV for that survey was multiplied by the RMSE and the model was refit. For example, if the RMSE equaled 1.5, each CV was multiplied by 1.5 (increasing the CVs by 50%) and the model was refit. This process was repeated until the RMSE agreed with expectations, which usually only required one iteration. CVs were not allowed to exceed 0.95 during this process.

An annual CV of 0.1 was assumed in all years for the catch from both fisheries. Although ad hoc, this value admits some uncertainty in the catches and does not force an exact fit.

Unconstrained annual recruitment deviations were estimated without any penalty for deviating from some underlying mean stock-recruit relationship. Previous assessments have estimated the parameters of a Beverton-Holt stock-recruit relationship, and penalized recruitment for deviating from this underlying curve (NEFSC 2012; Deroba 2015). This practice was not used here because a likelihood profile of steepness revealed that the data provided nearly no information about the correct value of steepness, and the model's ability to estimate steepness seemed to rely solely on a relatively high degree of negative correlation between steepness and unexploited SSB (correlation = -0.96; Figure B4- 8).

Catchability for all surveys was freely estimated.

ASAP base model diagnostics and results

The ASAP base model fit to the fishery catches closely with the scale of residuals being relatively small (Figure B4- 9). The residuals for both fleets, however, were characterized by sequences of positive or negative residuals that were unlikely to have occurred by random chance (Figure B4- 9). The iteratively reweighted ESS for both fisheries led to estimated mean ages in each year that were generally within the 95% confidence intervals of the observed mean ages (Figure B4- 10). Exceptions to this occurred early in the time series for the mobile fleet and in more recent years for the fixed fleet, most often in years with relatively low ESS (Figure B4- 10). Fits to the mobile gear age composition exhibited only a few sequences of patterned residuals (e.g., age 4 from 1989-2002) and had no obvious year class effects (Figure B4- 11). Fits to the fixed gear age composition generally did not exhibit any obvious runs of residuals except for some relatively large residuals for ages $\geq$ 4 during 1986-1991 (Figure B4- 11). The fixed gear fishery caught more fish at these ages during those years than is typical, although still a relatively small amount (TOR B1). Thus, these relatively large residuals are likely not problematic. The mobile gear fishery selectivity increased in a near linear fashion to age-7, when full selection began (Figure B4- 12). The fixed gear fishery selectivity increased from near 0.0 at age 1 to full selection at age 2 and then quickly declined at older ages (Figure B4- 12). Average selectivity was generally less than average maturity at age, with herring maturing prior to full selection (Figure B4- 13).

The ASAP base model fit the survey trends relatively well. With few exceptions, residuals for fits to the survey trends did not exhibit long runs of residuals and residuals were generally centered on zero (Figure B4- 14). The estimated log scale survey indices also generally fell within the 95% confidence intervals of the log scale observations (Figure B4- 14). With rare exception, the iteratively reweighted ESS for the surveys led to estimated mean ages in each year that were generally within the 95% confidence intervals of the observed mean ages (Figure B4- 15). Fits to the survey age compositions also generally did not exhibit patterns, with exceptions being some age effects (e.g., age 8 in the shrimp survey and spring 1985-2008; Figure B4- 16).

The CVs on estimates of catchability (q) among all the surveys ranged from 32% to 55%. The q for the NMFS spring survey between the 1968-1984 period and the 1985-2008 period increased by a factor of 3.8 (0.0000017 to 0.0000064; Figure B4- 17). The q for the NMFS spring survey between the 1985-2008 period and the 2009-2017 period increased by a factor of 5.7 (0.0000064 to 0.000037; Figure B4- 17). The q for the NMFS fall survey between the 1965-1984 period and the 1985-2008 period increased by a factor of 29 (0.00000035 to 0.0000101; Figure B4- 17). The q for the NMFS fall survey between the 1985-2008 period and the 2009-2017 period increased by a factor of 3.43 (0.0000101 to 0.000035; Figure B4- 17). The NMFS shrimp survey q equaled 0.0000099 and the q for the acoustic index equaled 0.000024 (Figure B4- 17). Whether the catchability changes estimated by the base ASAP model in the NMFS spring and fall surveys between the 1985-2008 period and the 2009-2017 period (i.e., Albatross to Bigelow time periods) are aliasing some other factors is unclear. But, a retrospective analysis of the base ASAP model using 17 peels showed the scale of the relative differences in SSB increasing as fewer years of data were used, which includes a general increase in the scale of the relative differences beginning in ~2009 (Figure B4- 18). This result may suggest that some other model mis-specification exists and could be aliased by the modeled changes in catchability. The retrospective pattern is likely to worsen as additional years of data are added to the base ASAP model structure.

No two parameters of the ASAP base model had correlations greater than 0.9 or less than -0.9. Log unexploited SSB was estimated to be 13.2 with a CV of 25%. Time series estimates of SSB, F (averaged over ages 7 and 8), and recruitment were estimated relatively precisely, with the exception of recruitment in 2016 and 2017 that had CVs of 100% and 252%, respectively (Figure B4- 19).

The base ASAP model estimated SSB in 2017 to be 141,473 mt, with SSB ranging from a minimum of 53,084 mt (1982) to a maximum of 1,352,700 mt (1967) over the entire time series (Figure B4- 20; Figure B4- 23; Table B4- 2). The base ASAP model estimated total January 1 biomass in 2017 to be 239,470 mt, ranging from a minimum of 169,860 mt (1982) to a maximum of 2,035,800 mt (1967) over the entire time series (Figure B4- 20; Table B4- 2).

No common age is fully selected in both the mobile and fixed gear fishery. Consequently, the average F between ages 7 and 8 was used for reporting results related to fishing mortality ($F_{7\text{-}8}$), and this includes reference points (see TOR B5). These ages are fully selected by the mobile gear fishery, which has accounted for most of the landings in recent years (TOR B1). $F_{7\text{-}8}$ in 2017 equaled 0.45. The all-time low of 0.13 occurred in 1965 (Figure B4- 23; Table B4- 2). The maximum $F_{7\text{-}8}$ over the time series equaled 1.04 (1975).

Age-1 recruitment has been below average since 2013 (Figure B4- 21; Figure B4- 22; Table B4- 2). The all-time high of 1.4 billion fish occurred in 1971. The estimates in 2009 and 2012 are still estimated to be relatively strong cohorts, as in previous assessments. The all-time low of 1.7 million fish occurred in 2016, and the second lowest of 3.9 million fish occurred in 2017. Four of the six lowest recruitment estimates have occurred since 2013 (2013, 2015, 2016, 2017).

Markov chain Monte Carlo (MCMC) simulation was performed to obtain posterior distributions of SSB and $F_{7\text{-}8}$ time series. An MCMC chain of length 6,000,000 was simulated with every 6000th value saved to create an MCMC chain with length 1,000 for defining the posterior densities. Traces and lag correlation plots for SSB and $F_{7\text{-}8}$ in 1965 and 2017 had no obvious irregularities and chains are presumed to have converged (Figure B4- 24; Figure B4- 25). The posteriors for SSB and $F_{7\text{-}8}$ in 1965 and 2017 are also provided as examples (Figure B4- 27). Time series plots of the 90% probability intervals are in Figure B4- 26while ASAP point estimates and the 80% probability intervals for SSB and $F_{7\text{-}8}$ in 2017 are below:

Metric	ASAP point estimate	80% probability interval
2017 SSB (mt)	141,473	114,281 - 182,138
2017 F7-8	0.45	0.32 - 0.57

Internal retrospective patterns were characterized by using 5 “peels” rather than the 7 peels that is more common because of the relatively few numbers of years available for the NMFS spring and fall bottom trawl surveys during years when only the Bigelow vessel was used (2009-2017). Using 7 peels would require estimating q parameters for these surveys based on 2-3 years of data for the last 2 peels, and this has caused large imprecision and non-convergence in other assessments (Atlantic mackerel; NEFSC 2018). The internal relative retrospective pattern suggested consistent overestimation of SSB with Mohn's Rho = 0.15, and underestimation of F_{7-8} with Mohn's Rho = -0.11 (Figure B4- 28). The retrospective pattern for recruitment at age 1 was characterized by both positive and negative peels, with all of the positive peels greater than 4 (Figure B4- 28). The presence of the retrospective pattern is sensitive to the indices used in the ASAP base model (see sensitivity below with no acoustic index).

Estimates of SSB and fishing mortality among assessments from 1995, 2005, 2009, 2012, 2015, and the current ASAP base model were compared. Exact values from an assessment in 1998 were unavailable, but graphical representations of that assessment were similar in trend and scale as the 1995 assessment. The range of ages over which fishing mortality was calculated differed among assessments, as did selectivity, and therefore F values are not directly comparable, but were still useful for examining temporal trends. Estimates of SSB diverged among assessments more so at the beginning and end of the time series, with more similarity in intermediate years (~1970-1988; Figure B4- 29). Assessments in 1995 and 1998, however, estimated SSB to be about four times higher in the mid-1990s than assessments in 2005-2018 (Figure B4- 29). This contrast can be explained by a switch from a VPA model in 1995 and 1998 to an ASAP model for the other assessments. Estimates of SSB since about 2000 have generally decreased in each subsequent assessment (Figure B4- 29). Estimates of F from all the assessments were similar to that of SSB, except with differences occurring in the opposite direction; F generally increasing since 2000 in each subsequent assessment (Figure B4- 29). Changes in input data (e.g., acoustic index, time varying maturity) and model structure (e.g., M, selectivity) have occurred among assessments, and so the results for SSB and F are not entirely comparable.

ASAP base model sensitivity runs

In each of the sensitivity runs described below, all of the data and settings in the base model were the same as described above, except for the changes required for the given sensitivity run. Results focused on SSB because changes induced by the sensitivity runs were similar for F except in the opposite directions. Results also focused on retrospective patterns, and when appropriate, likelihood values.

ASAP base model sensitivity – M

Amending the ASAP base model to have age- and time-varying M as in previous assessments (NEFSC 2012; Deroba 2015) using the combination of Hoenig and Lorenzen methods (Hoenig 1983; Lorenzen 1996; Brodziak et al 2011) and a 50% increase in those values during 1996-2017, increased the scale of SSB and recruitment (Figure B4- 30). The retrospective pattern was similar between this sensitivity and the base model (Figure B4- 28; Figure B4- 31). The fit of the model was 5 likelihood units better than the base.

Eliminating the 50% increase in M during 1996-2017 and basing M only on the combination of Hoenig and Lorenzen methods, reduced the scale of SSB relative to the base (Figure B4- 32). The retrospective pattern was similar between this sensitivity and the base model (Figure B4- 28; Figure B4- 33). The fit of the model was similar (1likelihood unit worse) to the base.

ASAP base model sensitivity – calibrate Bigelow to Albatross

Calibrating the spring and fall NMFS bottom trawl surveys collected with the Bigelow vessel (2009-2017) to Albatross vessel equivalents using results from the paired tow experiments (Miller et al. 2010; NEFSC 2012) increased the scale of SSB relative to the base (Figure B4- 34). The retrospective pattern was also worse relative to the base, with Mohns's Rho equal to 0.34 for SSB and -0.24 for $F_{7\text{-}8}$ (Figure B4- 28Figure B4- 35). The base ASAP model estimated a 5.7 fold increase in catchability in the spring between the Bigelow and the Albatross, and a 3.4 fold increase in the fall (Figure B4- 36). These changes are 61% larger than the changes in catchability estimated by the paired tow experiments for the spring, and 73% larger for the fall (Figure B4- 36), and this explains the scale shift between the base model and using the paired tow calibrations.

ASAP base model sensitivity –time varying mobile fleet selectivity

The Working Group had concerns that the purse seine gear had a distinct selectivity from trawl gears, but these gears were combined in the mobile gear fleet (see TOR B1). To address this concern, time varying selectivity was added to the mobile gear fleet in the form of separate selectivity blocks for 1965-1990 and 1991-2017, where the break occurs in a year when purse seine catches decreased relative to the trawl gears and remained so. Selectivity at age in both blocks was freely estimated for ages 1-6, but fixed at 1.0 for ages 7-8. The model with 2 selectivity blocks improved model fit by 4 likelihood units over the base model, but also estimated 6 more parameters than the base (AIC would not support the 2 blocks). The model with 2 selectivity blocks also had qualitatively similar residuals as the base, nearly indistinguishable estimates of SSB, and the retrospective patterns were also similar (Figure B4-28; Figure B4- 37; Figure B4- 38).

ASAP base model sensitivity–drop surveys ("leave one out")

The base ASAP model was re-run with each of the surveys removed from the model. The point estimates of SSB from each of the surveys remained within the 95% confidence intervals of the base run (Figure B4- 39). In more recent years, the base model was most sensitive to the exclusion of the acoustic index, with removing the acoustic index reducing the scale of SSB relative to the base (Figure B4- 39). Exclusion of the acoustic survey also eliminated the retrospective pattern, with peels for SSB and $F_{7\text{-}8}$ being both positive and negative (Figure B4- 40). The model was also less precise without the acoustic index, as evidenced by wider confidence intervals on stock status when compared to the base (Figure B4- 41Figure B6-1). Stock status would also change in a model without the acoustic index, with overfishing occurring (Figure B4- 41).

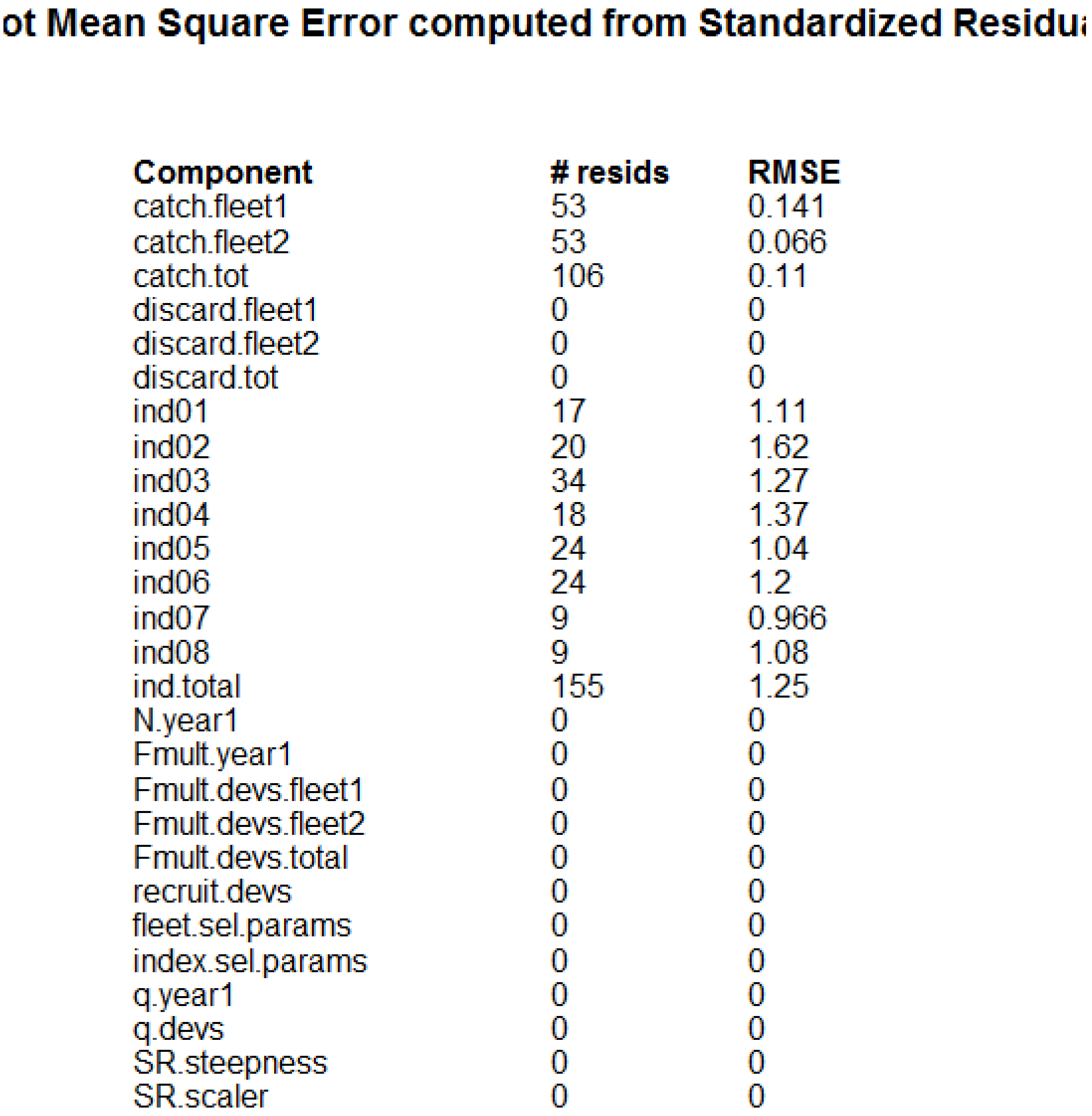
ASAP base model sensitivity–fit with food habits index of abundance

The base model fit with the addition of the food habits index of abundance provided similar time series estimates of SSB (and F and recruitment) as the base model (Figure B4- 42). The fit to the food habits index was characterized by mostly negative residuals before ~1995 and mostly positive residuals after ~1995, although the estimated indices were generally within the 95% confidence intervals of the log scale observations (Figure B4- 43). The retrospective pattern was similar to the base (not shown).

ASAP base model sensitivity runs–explaining the scale difference from 2015

These sensitivities demonstrate that the shift in scale from the 2015 operational assessment (Deroba 2015) is a combination of: 1) basic data updates, with the retrospectively adjusted SSB value from 2015 being similar to that of the 2015 assessment updated through 2017, 2) treating the NMFS spring and fall bottom trawl surveys in years sampled by the Bigelow (2009-2017) as a separate index time series, 3) using a constant M as opposed to an age- and time-varying M, and 4) to a lesser extent than the other model changes, new data sources such as the acoustic index.

Table B4- 1 Root mean squared error table for the base Atlantic herring ASAP model, after iteratively reweighting



ot Mean Square Error computed from Standardized Residu

Component	# resids	RMSE
catch.fleet1	53	0.141
catch.fleet2	53	0.066
catch.tot	106	0.11
discard.fleet1	0	0
discard.fleet2	0	0
discard.tot	0	0
ind01	17	1.11
ind02	20	1.62
ind03	34	1.27
ind04	18	1.37
ind05	24	1.04
ind06	24	1.2
ind07	9	0.966
ind08	9	1.08
ind.total	155	1.25
N.year1	0	0
Fmult.year1	0	0
Fmult.devs.fleet1	0	0
Fmult.devs.fleet2	0	0
Fmult.devs.total	0	0
recruit.devs	0	0
fleet.sel.params	0	0
index.sel.params	0	0
q.year1	0	0
q.devs	0	0
SR.steepness	0	0
SR.scaler	0	0

Table B4- 2 Time series estimates of Atlantic herring from the base ASAP model

Year	SSB (mt)	Jan.1 Biomass (mt)	Age-1 Recruitment (000s)	$F_{7\text{-}8}$
1965	822530	1684170	5455740	0.13
1966	1158280	1908910	4582210	0.22
1967	1352730	2035820	9893020	0.36
1968	879319	1757780	4584770	0.64
1969	558945	1252230	5314820	0.66
1970	495252	990597	2726970	0.65
1971	309278	939626	14034800	0.97
1972	256642	941744	2487340	0.92
1973	421291	933513	2480520	0.89
1974	358470	694550	3080770	0.84
1975	234402	520342	1870600	1.04
1976	179914	390076	1889890	0.69
1977	107066	290770	5610910	0.70
1978	78307	348807	5312970	0.83
1979	72862	369009	760023	0.60
1980	86845	252059	3951690	0.99
1981	75400	183556	2123520	0.60
1982	53084	169857	1877800	0.64
1983	70978	183135	1371520	0.53
1984	64660	205018	4522510	0.89
1985	72605	212830	3327060	0.57
1986	103420	326508	3045410	0.46
1987	150558	389461	4230370	0.56
1988	253638	481774	6570600	0.61
1989	189046	653702	7616190	0.66
1990	182758	730272	8262200	0.42
1991	302782	834362	6996250	0.43
1992	452094	900893	3420850	0.40
1993	442046	851067	3432600	0.31
1994	389308	751971	4041110	0.26
1995	366549	848662	11221100	0.41
1996	433942	885059	5024520	0.44
1997	310950	861261	4848000	0.44
1998	447860	805422	3131950	0.38
1999	414034	840145	7791940	0.41
2000	394747	833338	2062680	0.37
2001	411161	796936	2067110	0.42
2002	332243	698200	4638660	0.38
2003	264895	684761	5505720	0.47
2004	240243	625565	2896810	0.48
2005	307228	560570	2036360	0.47
2006	260012	557285	4272270	0.58
2007	196392	503615	1229030	0.56
2008	207711	444931	2712310	0.58
2009	139353	577250	10579800	0.94
2010	121661	519530	2364220	0.72
2011	185013	500048	2110360	0.61
2012	243767	602132	6941730	0.60
2013	210106	580801	1370270	0.65
2014	330492	547060	1608170	0.51
2015	264982	471603	776348	0.47
2016	175698	347230	174758	0.47
2017	141473	239472	392286	0.45

Figure B4- 1 Retrospective pattern for the 2015 ASAP operational herring assessment updated using data through 2017

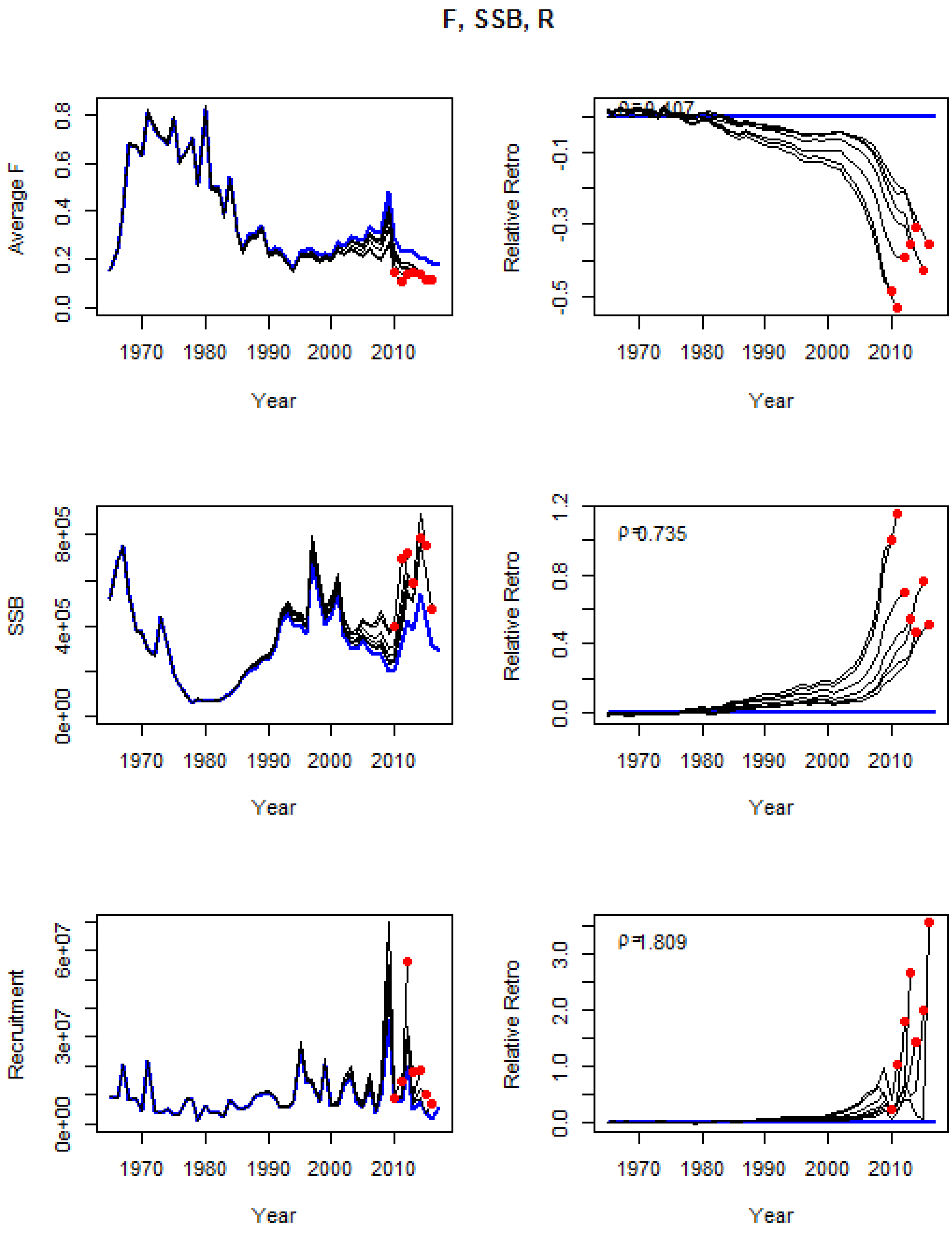


Figure B4- 2 Results of updating the 2015 ASAP operational herring assessment (2015FixFall) with data through 2017 (Run1_2017). The black diamond is the retrospectively adjusted SSB value from 2015.

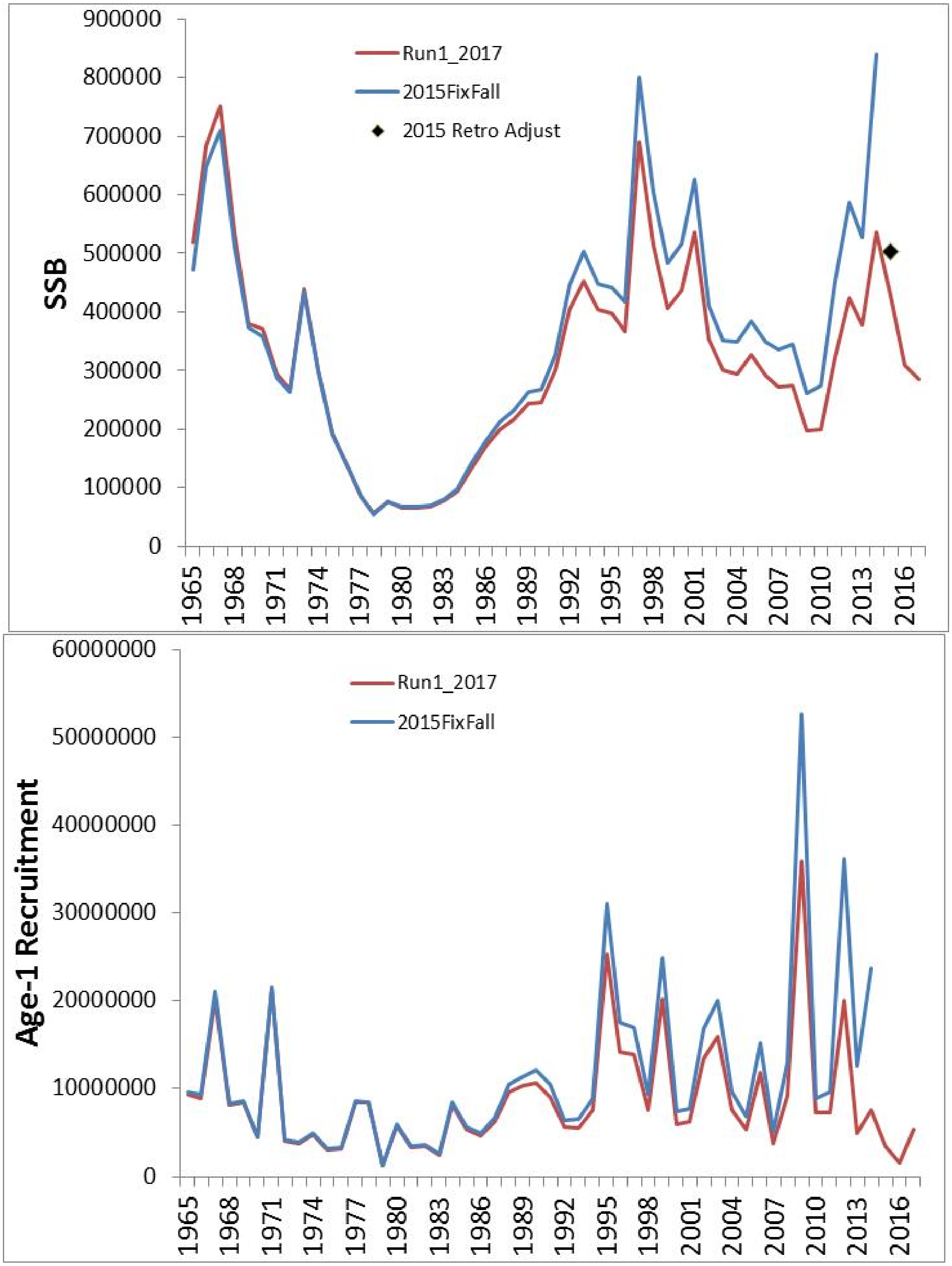


Figure B4- 3 Consumption of Atlantic herring by piscivorous predators as estimated using food habits data (Food Habits), and the amount of herring dying to due natural mortality in the ASAP base model (ASAP)

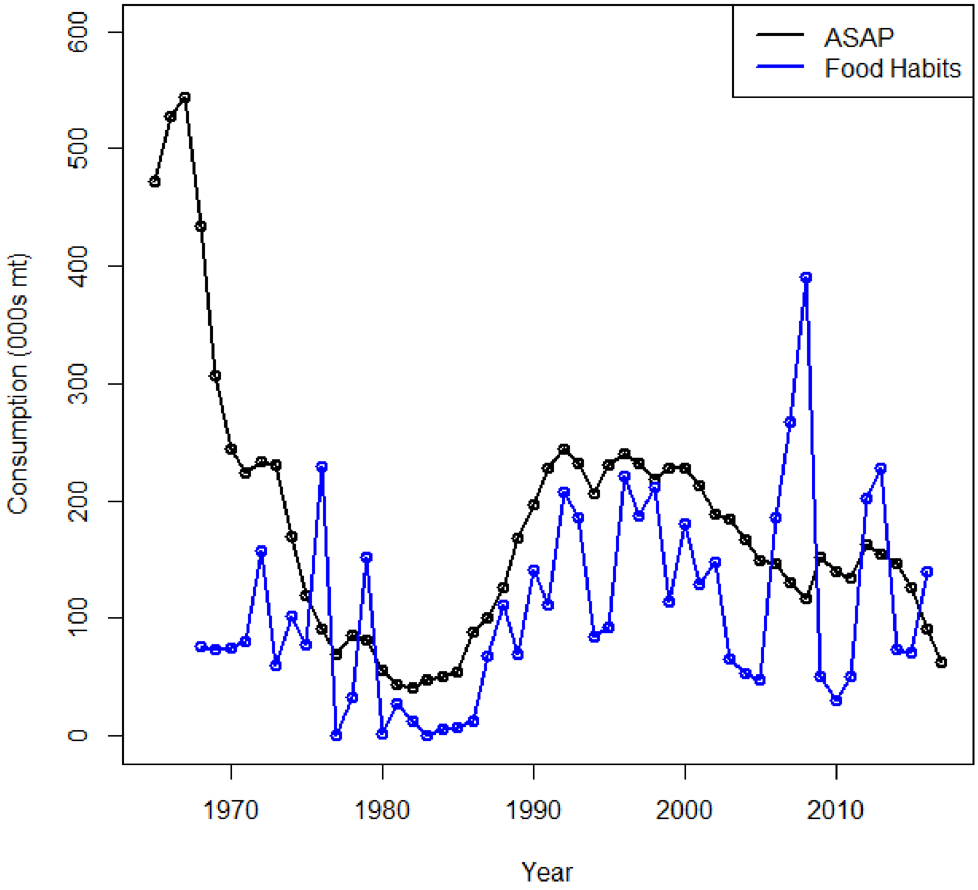


Figure B4- 4 Likelihood profile over time- and age-invariant natural mortality values for the base Atlantic herring ASAP model

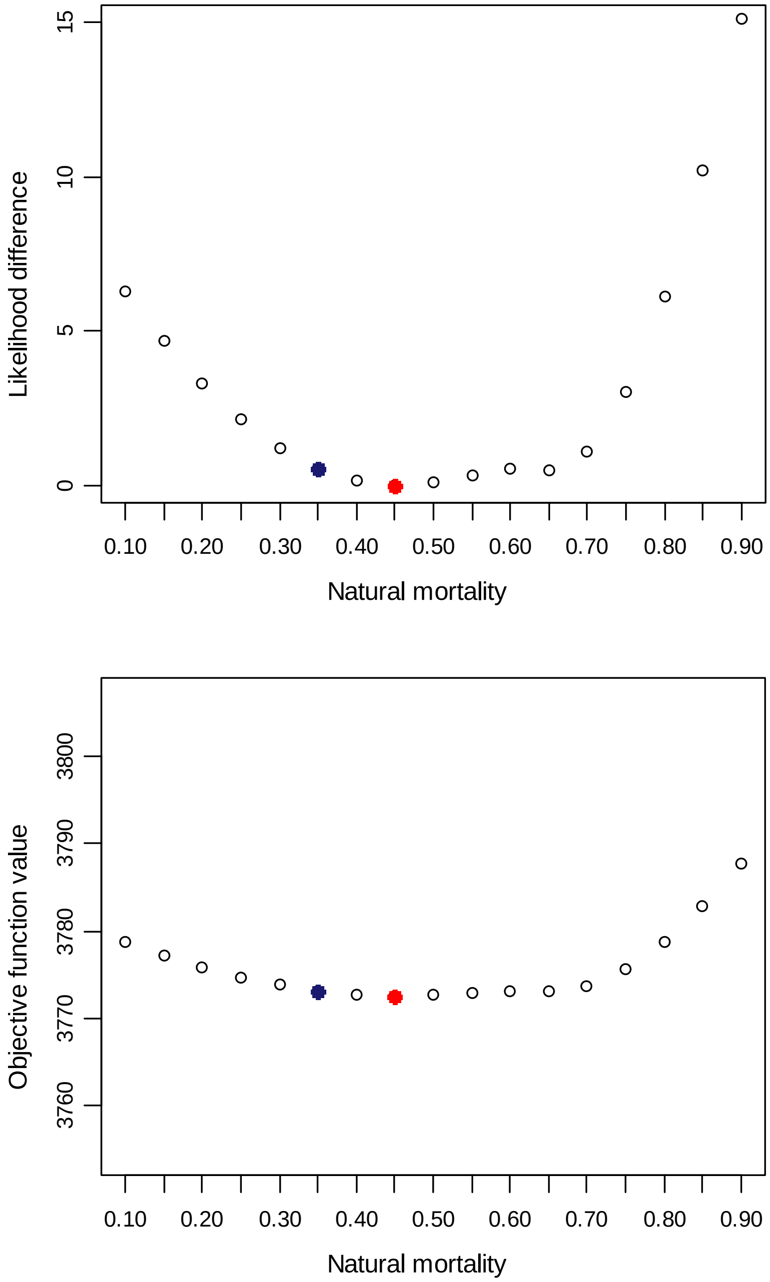
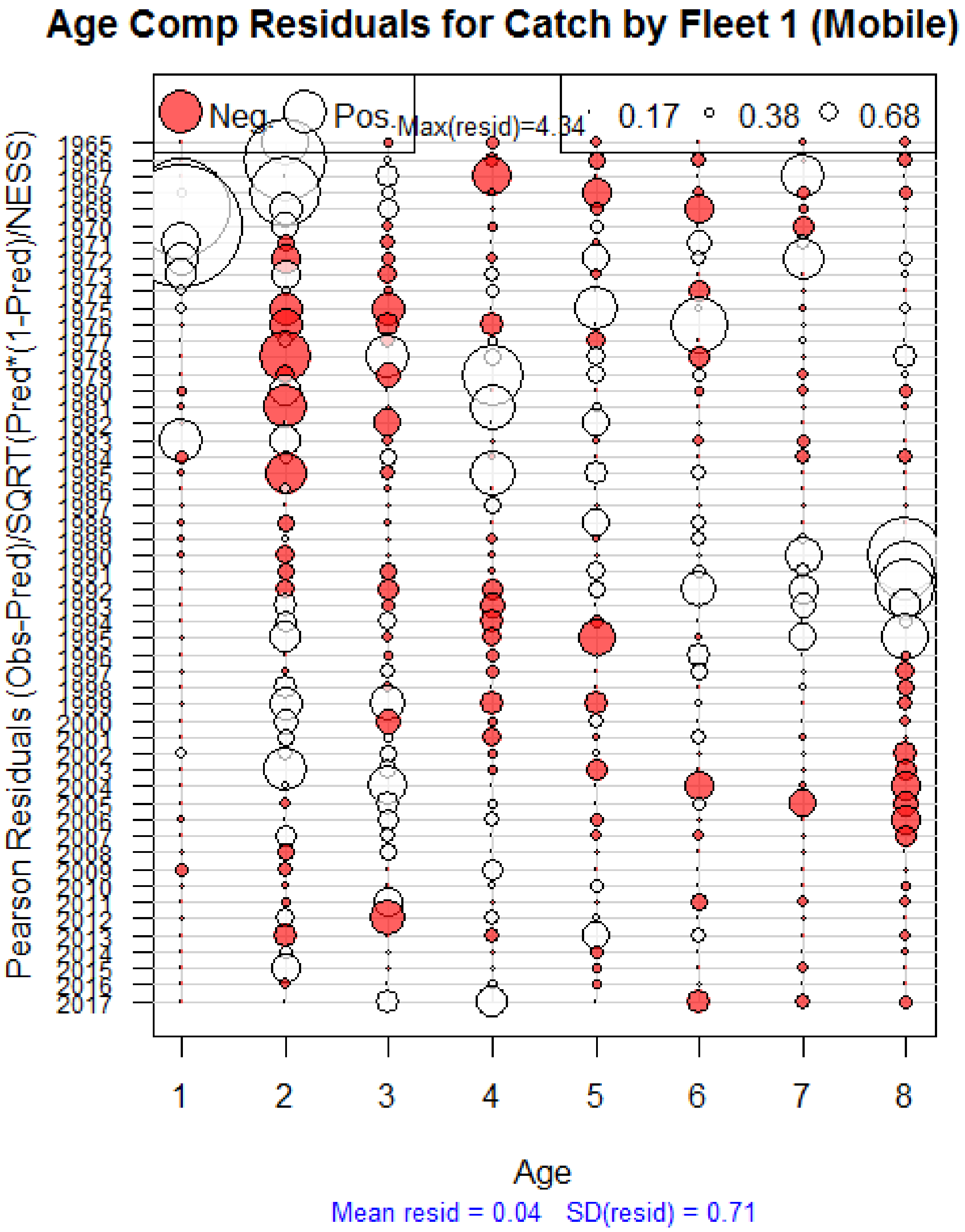


Figure B4- 5 Fits to Atlantic herring age composition for the mobile fleet from the base ASAP model (top panel) and from a fit with the mobile fleet selectivity at ages 5 and 6 fixed at 1.0 (bottom panel)



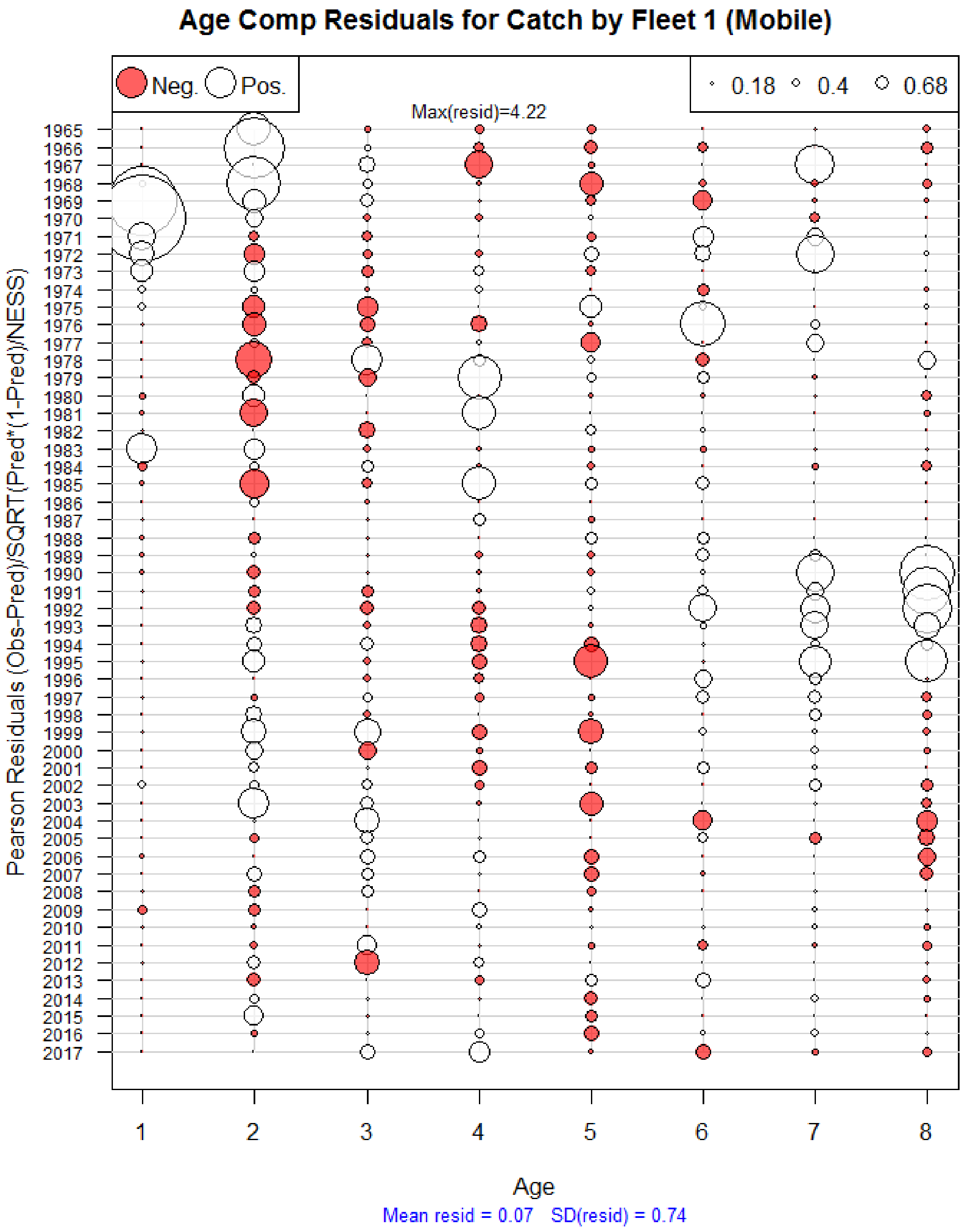
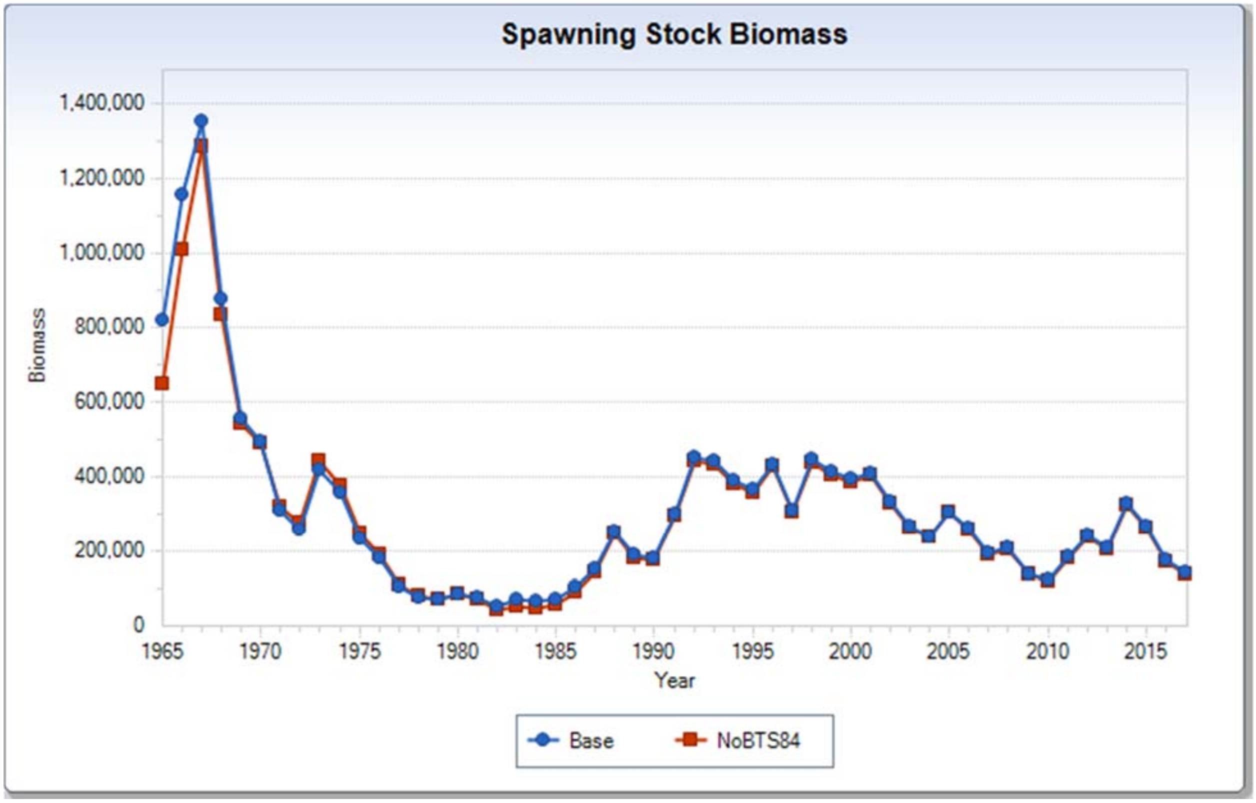

Age Comp Residuals for Catch by Fleet 1 (Mobile)
Neg.
Pos.
0.18
0.4
0.68
Max(resid)=4.22
Pearson Residuals (Obs-Pred)/SQRT(Pred*(1-Pred)/NESS)
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
1
2
3
4
5
6
7
8
Age
Mean resid = 0.07 SD(resid) = 0.74

Figure B4- 6 Effect of inclusion (Base) or exclusion (NoBTS84) of the NMFS spring and fall bottom trawl surveys during ≤1984



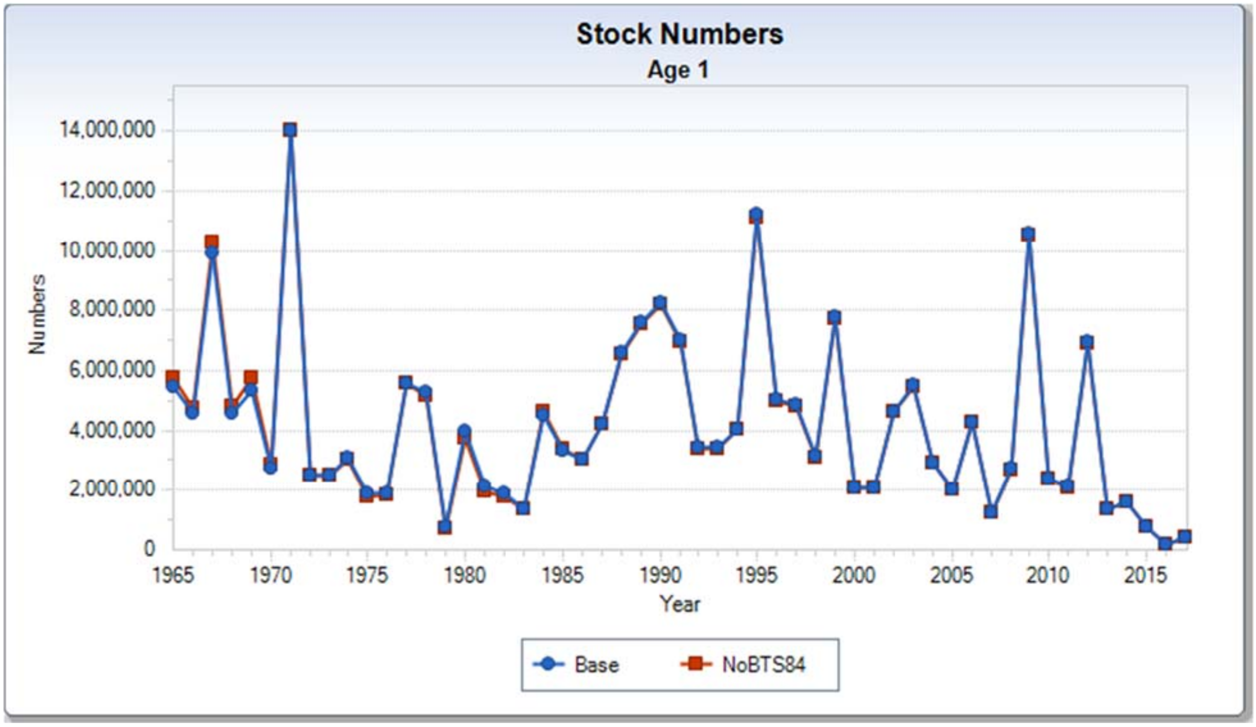


Figure B4- 7 RMSE of the indices after iteratively reweighting in the base ASAP model

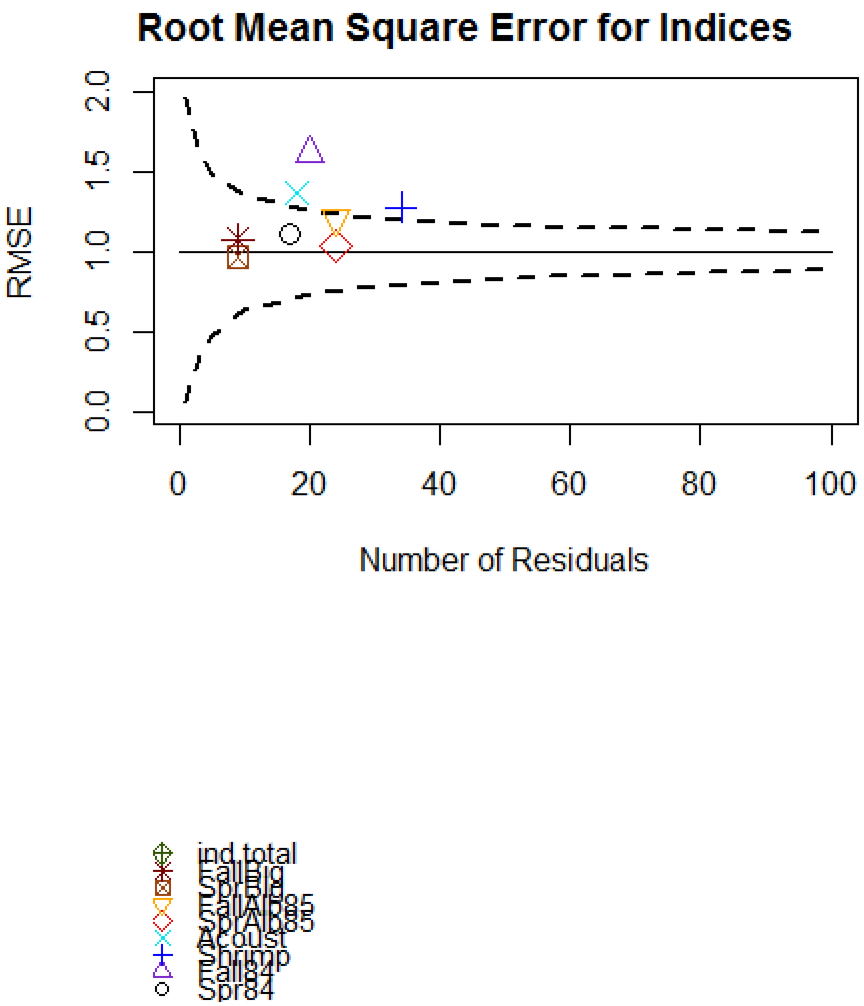


Figure B4- 8 Likelihood profile over steepness for the base ASAP model.

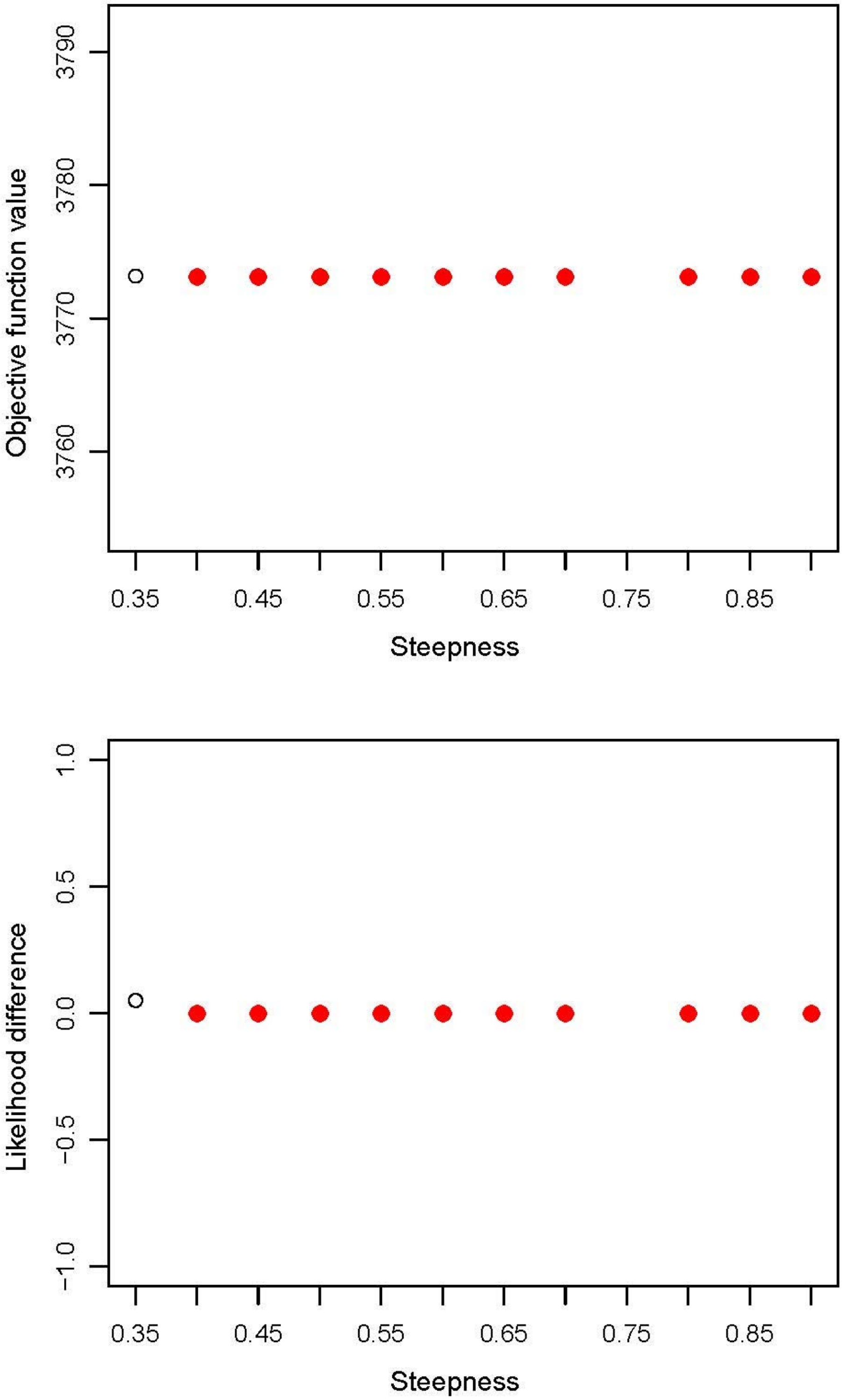
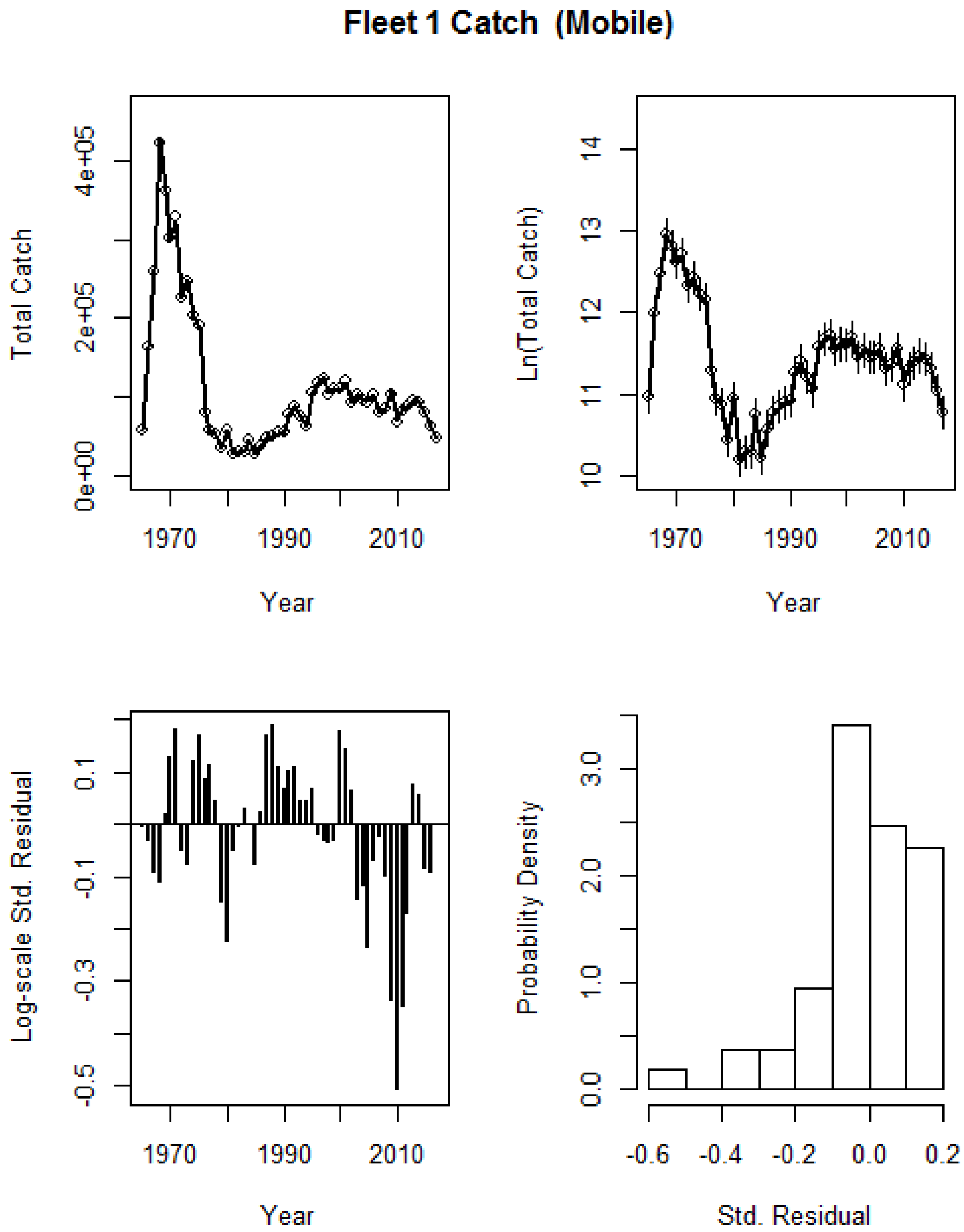


Figure B4- 9 Fits to Atlantic herring catch (mt) for the mobile (top panel) and fixed (bottom panel) fleets from the fit of the base ASAP model



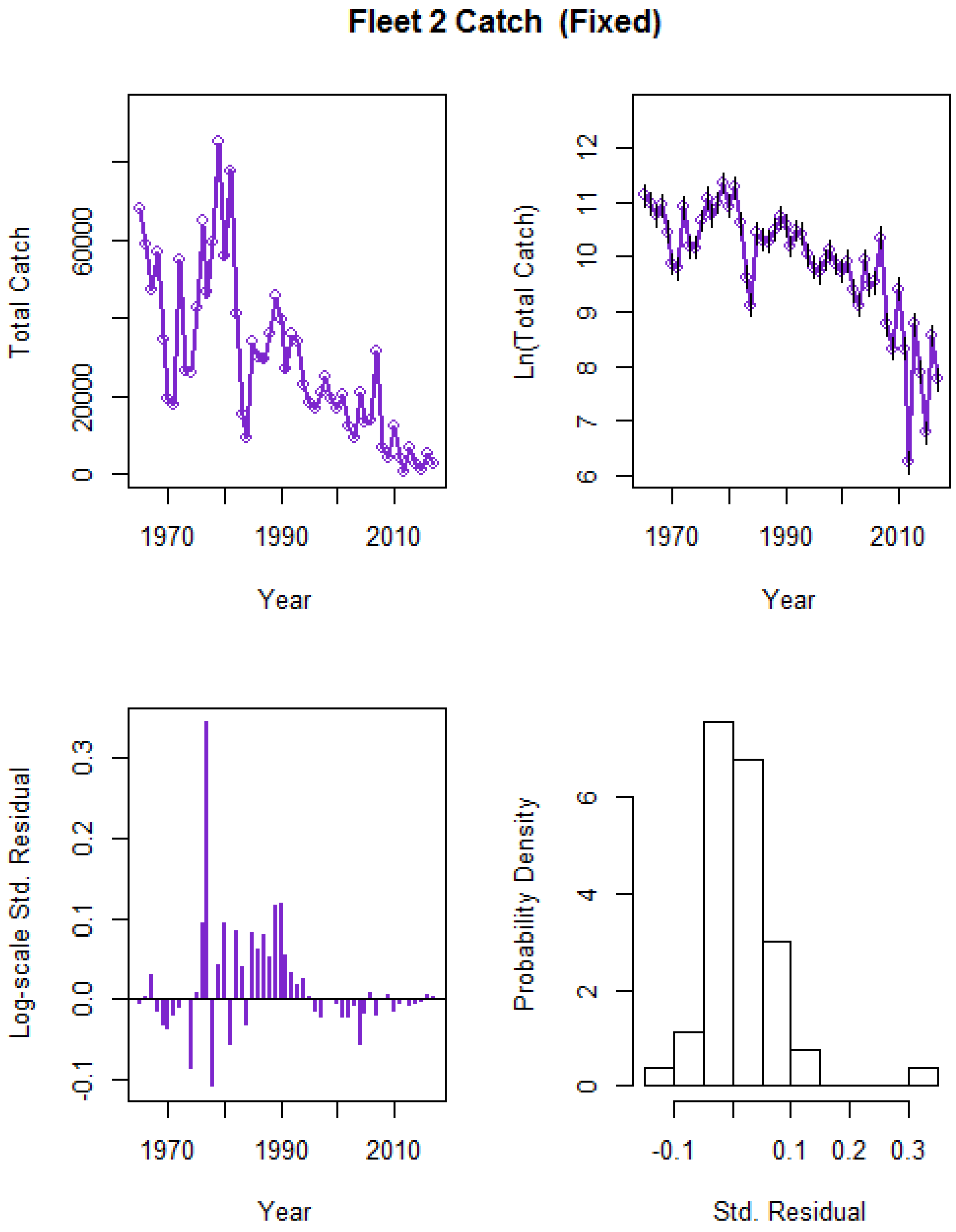
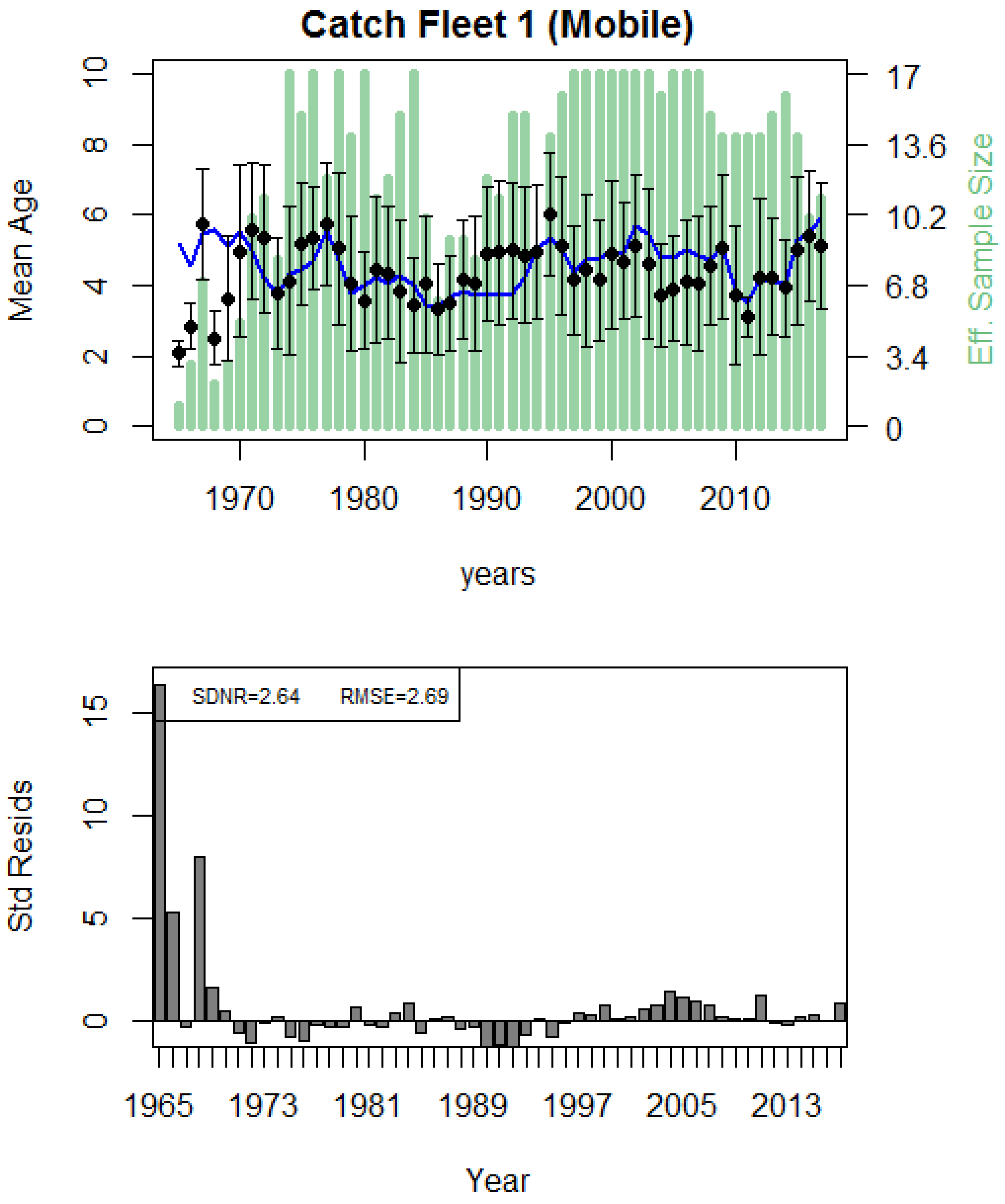
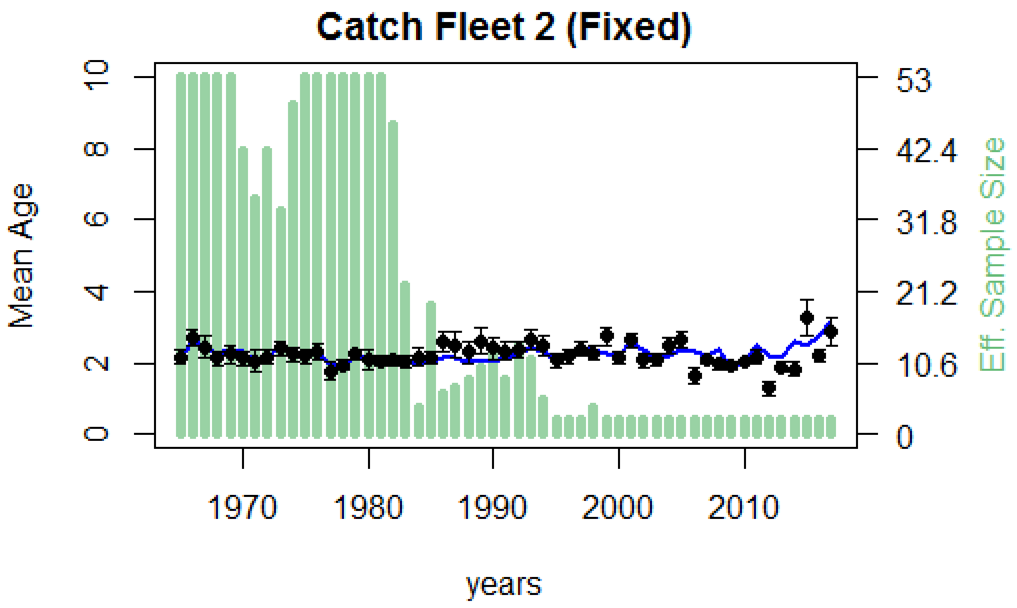

Fleet 2 Catch (Fixed)
Total Catch
0
20000
60000
1970
1990
2010
Year
Ln(Total Catch)
6
7
8
9
10
11
12
1970
1990
2010
Year
Log-scale Std. Residual
-0.1
0.0
0.1
0.2
0.3
1970
1990
2010
Year
Probability Density
0
2
4
6
-0.1
0.1
0.2
0.3
Std. Residual

Figure B4- 10 Fits to Atlantic herring mean age and standardized residuals for the mobile (top panel) and fixed (bottom panel) fleets from the fit of the base ASAP model




Catch Fleet 2 (Fixed)
Mean Age
0
2
4
6
8
10
Eff. Sample Size
0
10.6
21.2
31.8
42.4
53
1970
1980
1990
2000
2010
years

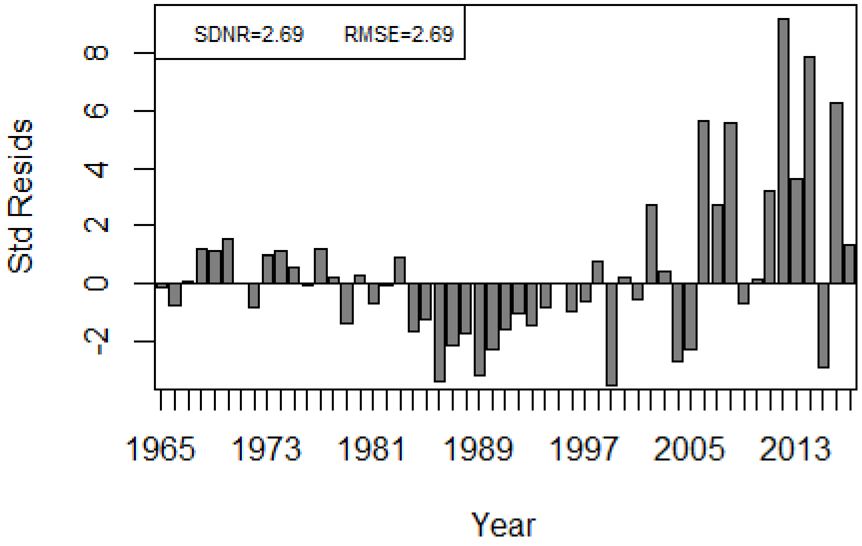
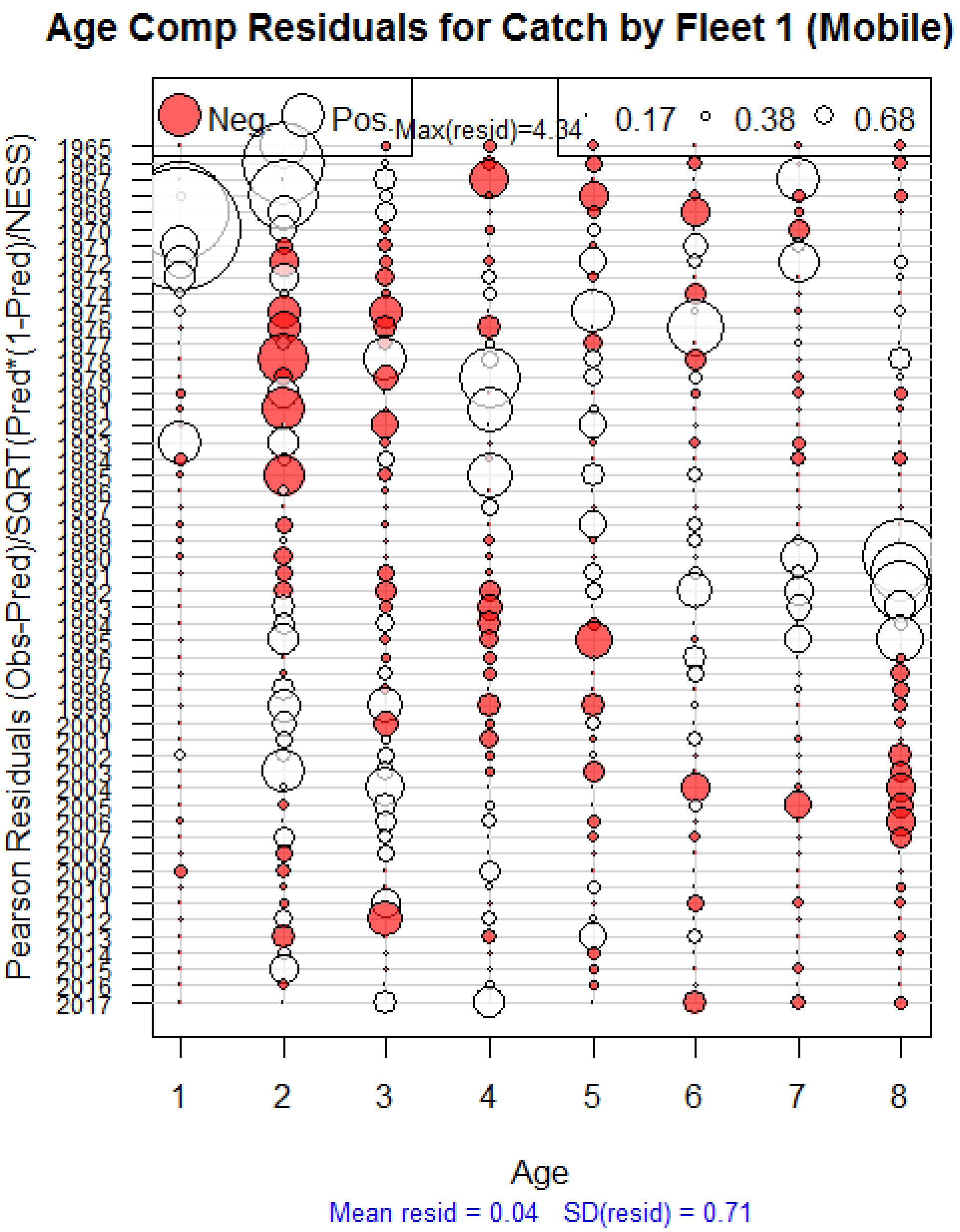

SDNR=2.69
RMSE=2.69
Std Resids
-2
0
2
4
6
8
1965
1973
1981
1989
1997
2005
2013
Year

Figure B4- 11 Fits to the Atlantic herring age compositions for the mobile (top panel) and fixed (bottom panel) fleets from the base ASAP model



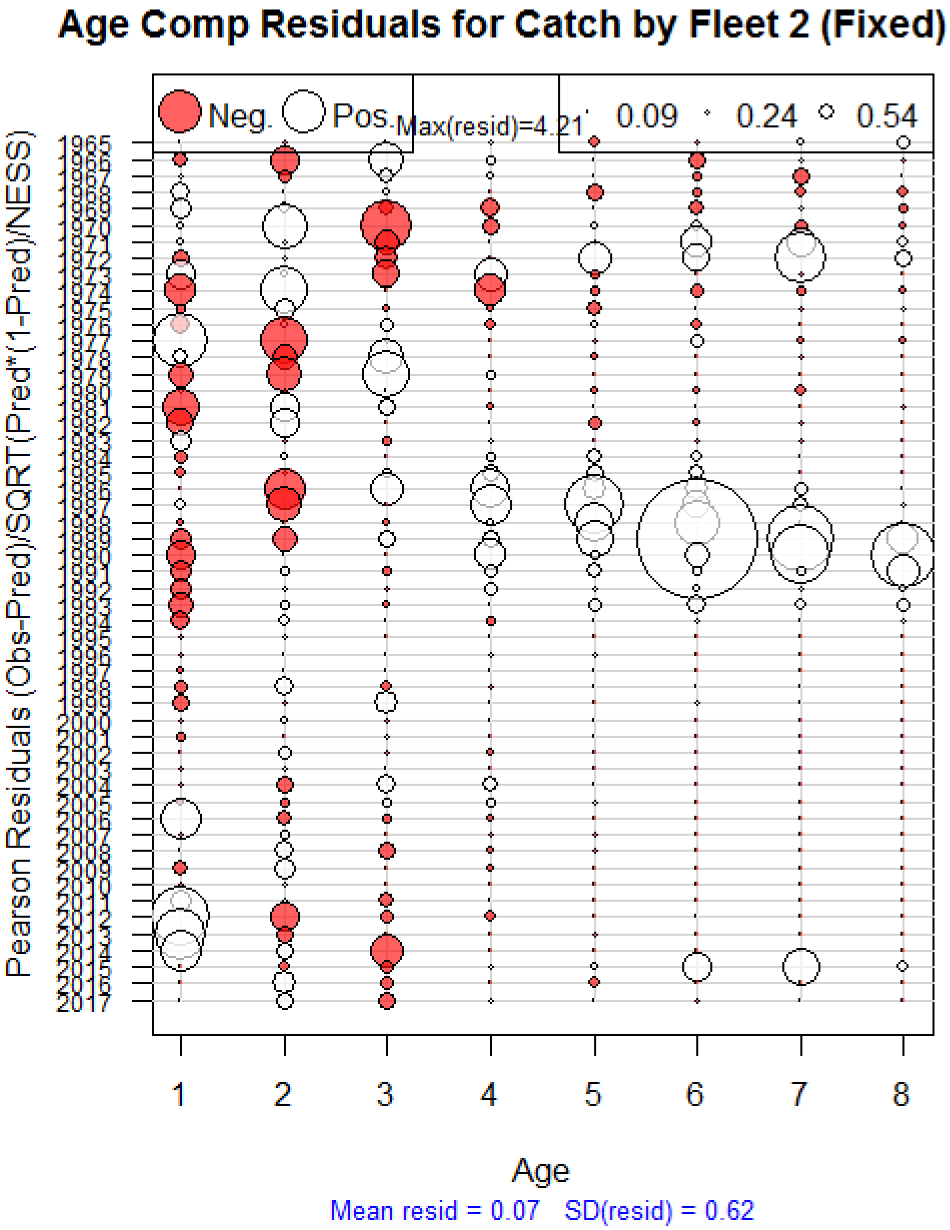
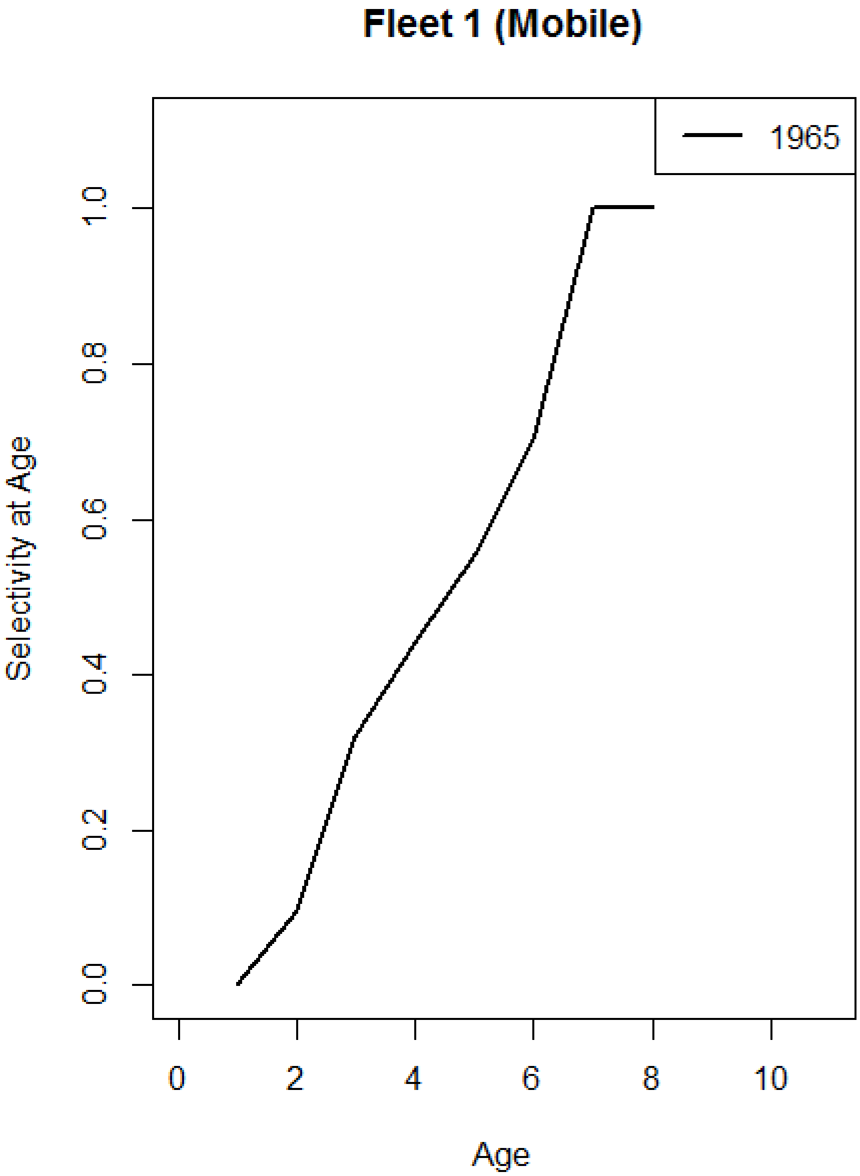

Age Comp Residuals for Catch by Fleet 2 (Fixed)
Neg.
Pos.
Max(resid)=4.21
0.09
0.24
0.54
Pearson Residuals (Obs-Pred)/SQRT(Pred*(1-Pred)/NESS)
1965
2017
1
2
3
4
5
6
7
8
Age
Mean resid = 0.07   SD(resid) = 0.62

Figure B4- 12 Selectivity for the mobile (top panel) and fixed (bottom panel) fleets from the base ASAP model



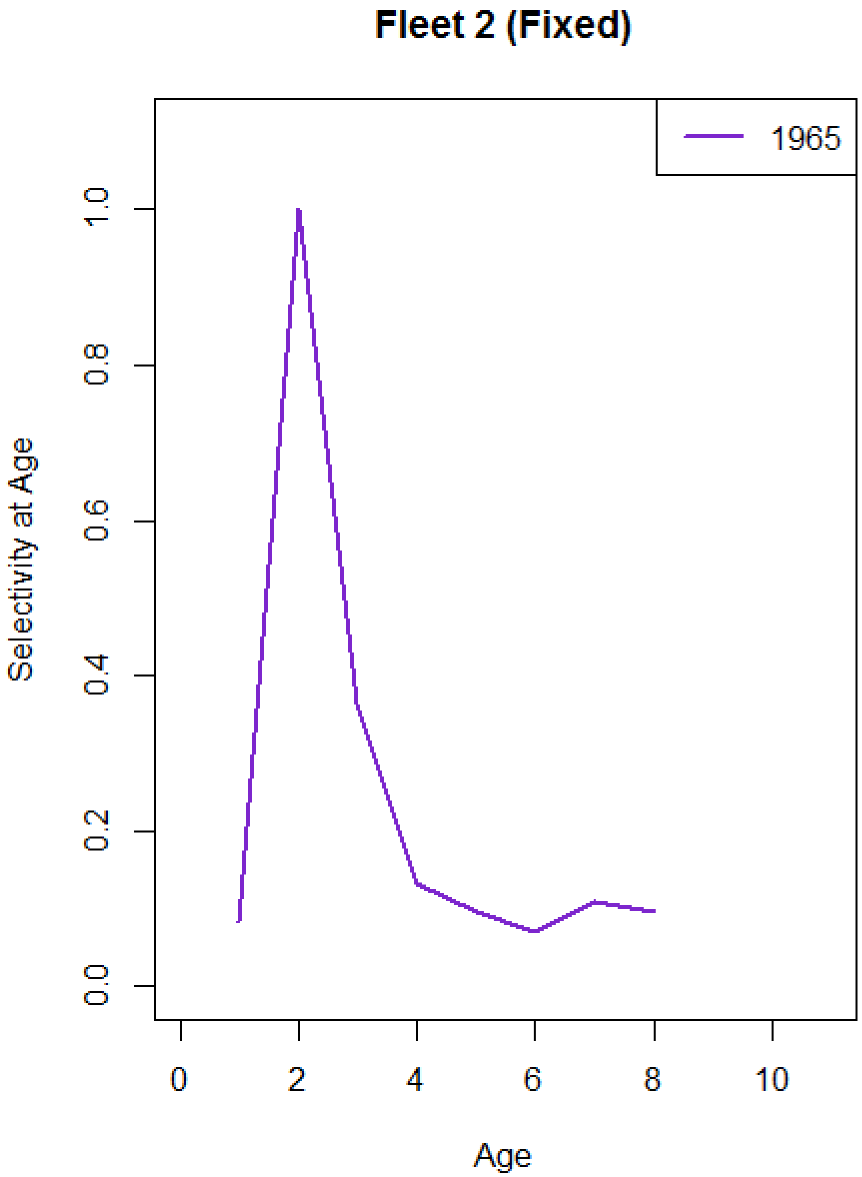

Fleet 2 (Fixed)
1965
Selectivity at Age
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
Age

Figure B4- 13 Average selectivity and terminal year maturity at age from the base ASAP model

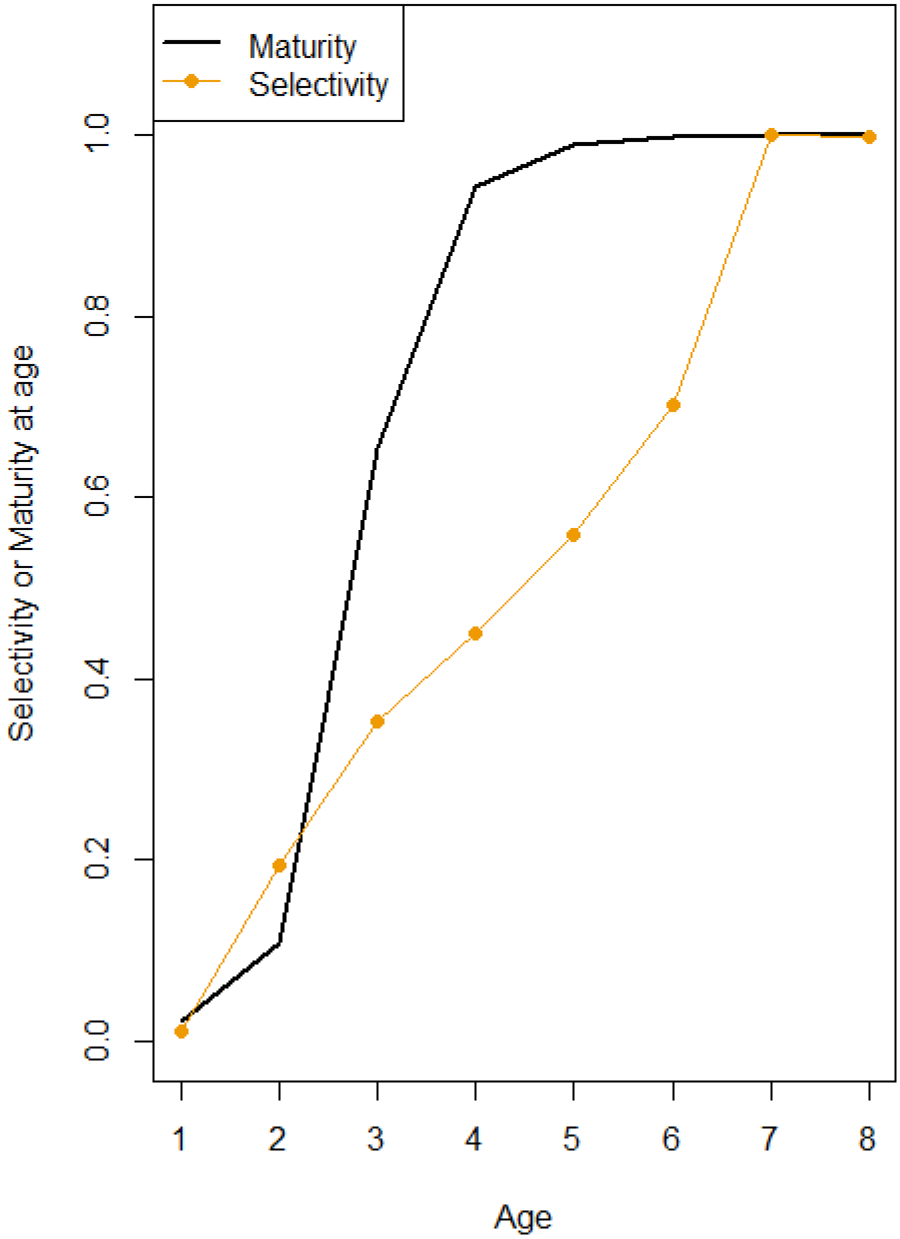
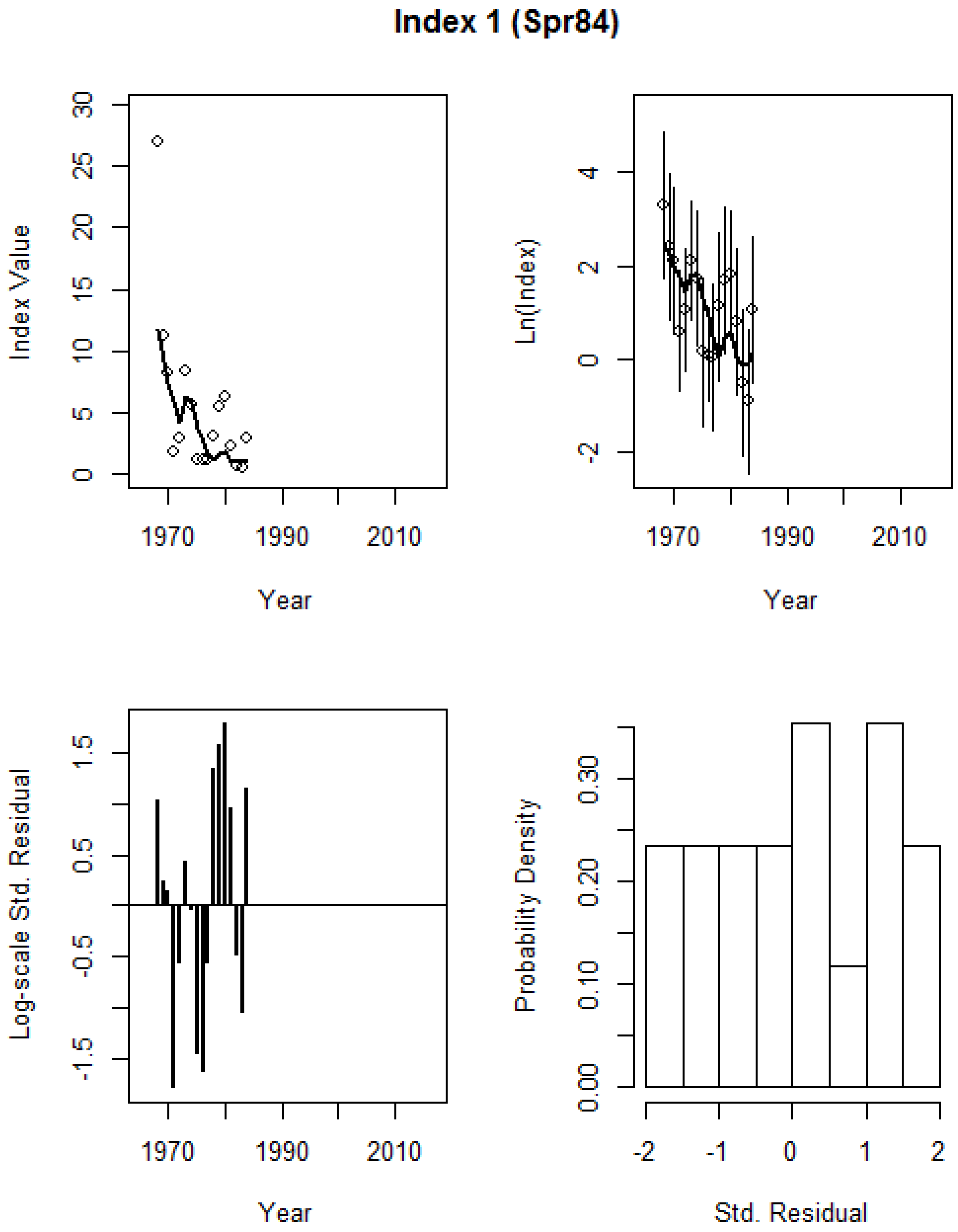
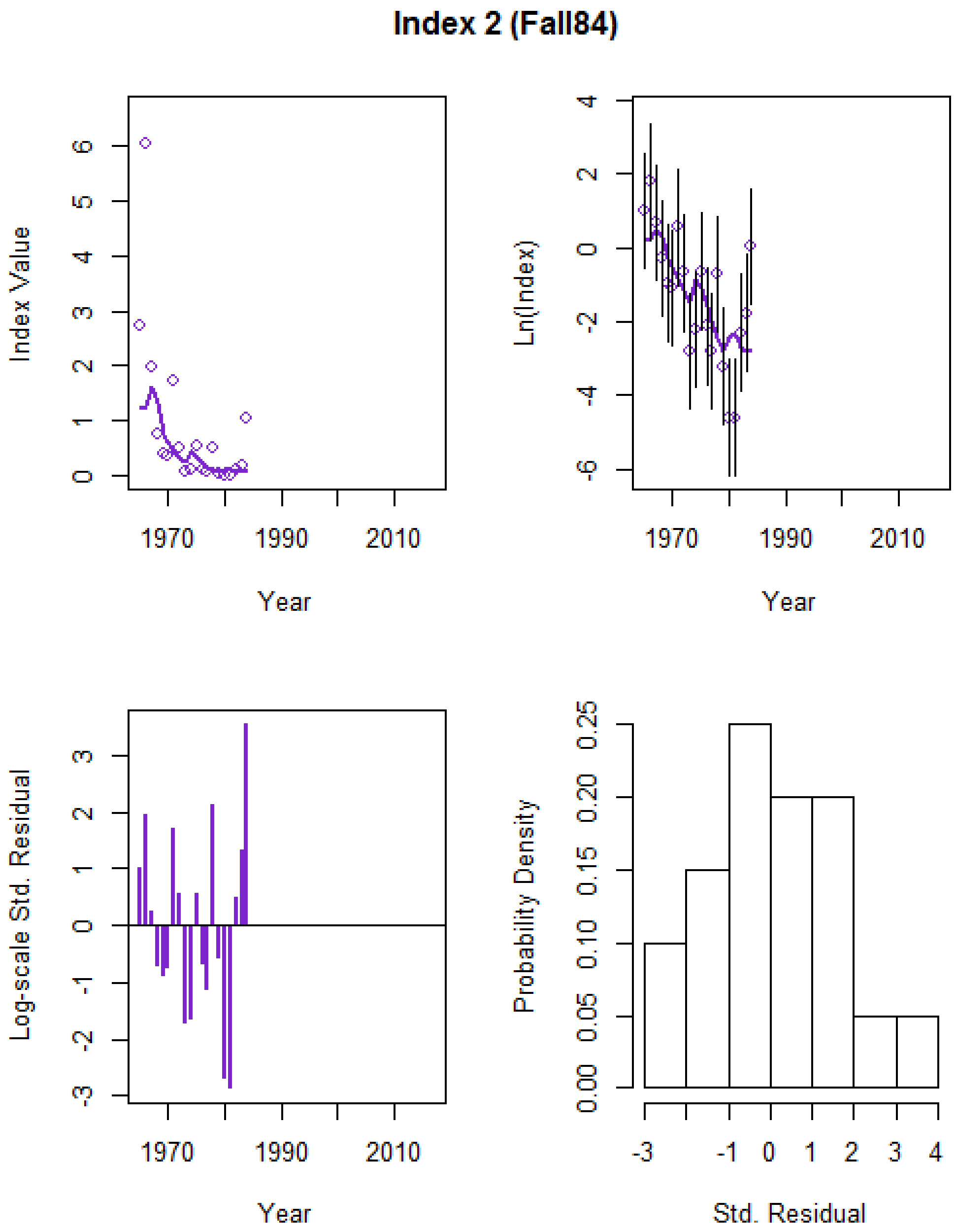
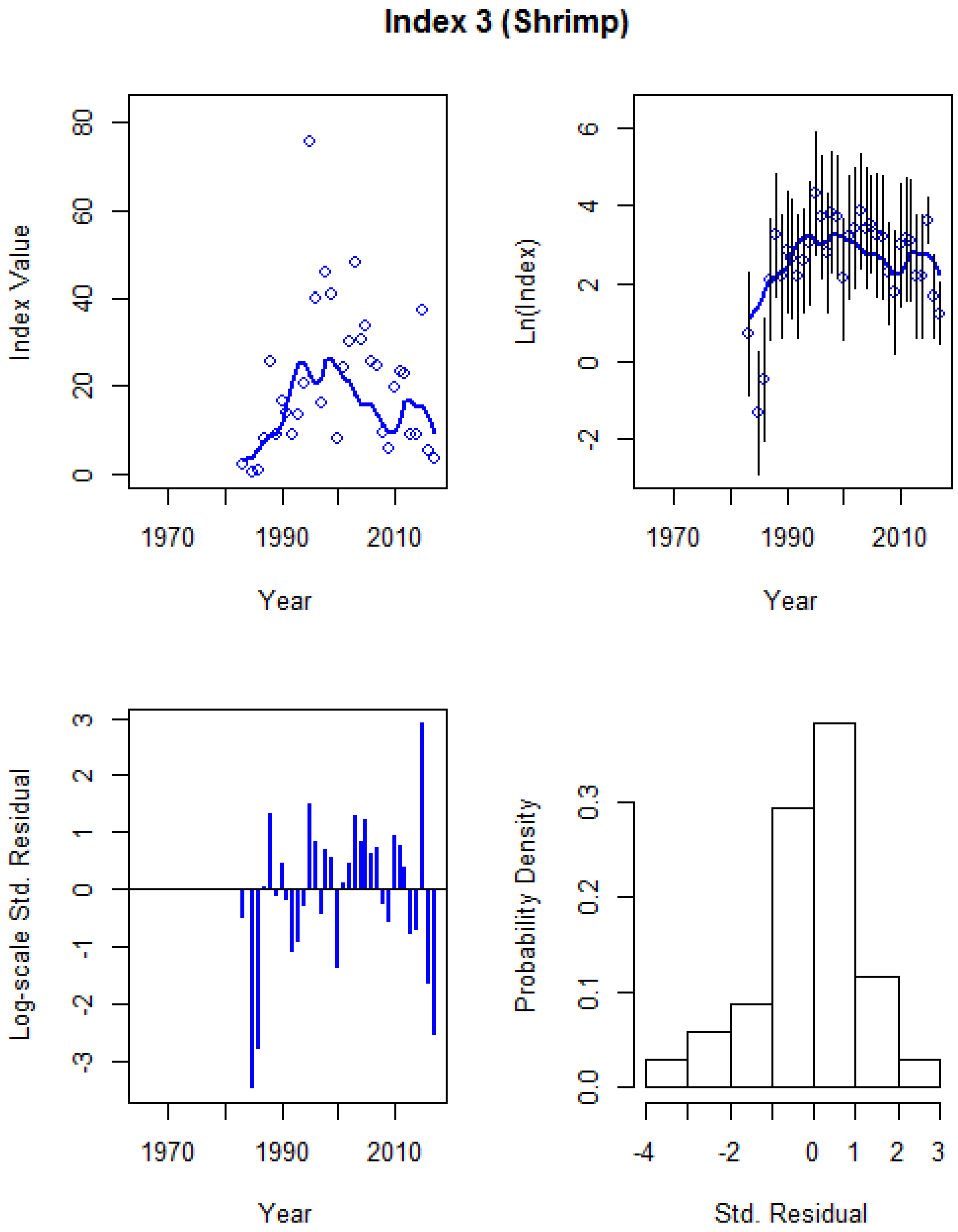
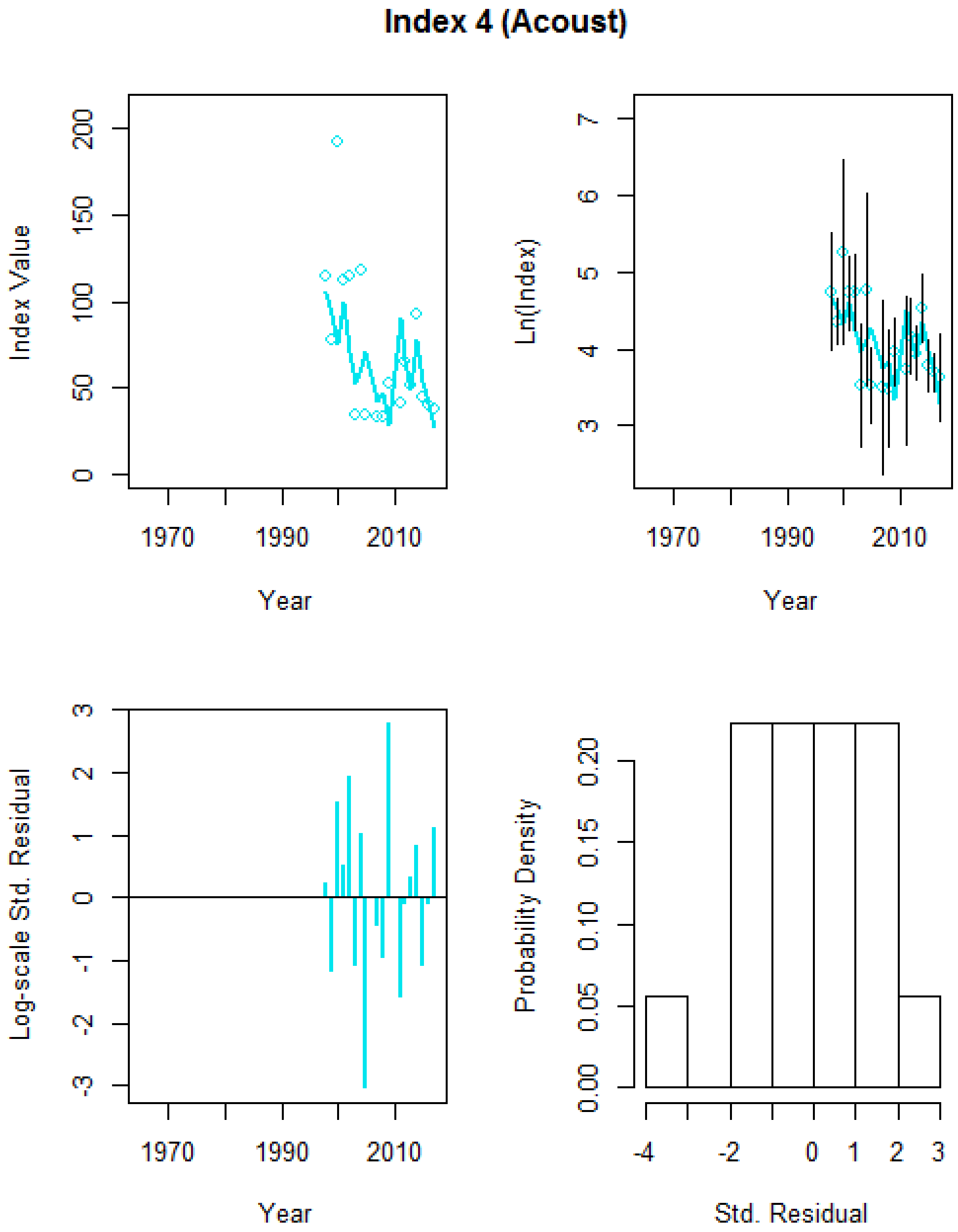


Figure B4- 14 Fits to indices for the base ASAP model (Spr84: Albatross 1965-1984; Fall84: Albatross 1965-1984; Shrimp: NMFS summer/shrimp; Acoust: NMFS acoustic index; Spr85: Albatross 1985-2008; Fall85: Albatross 1985-2008; SprBig: Bigelow 2009-2017; FallBig: Bigelow 2009-2017)

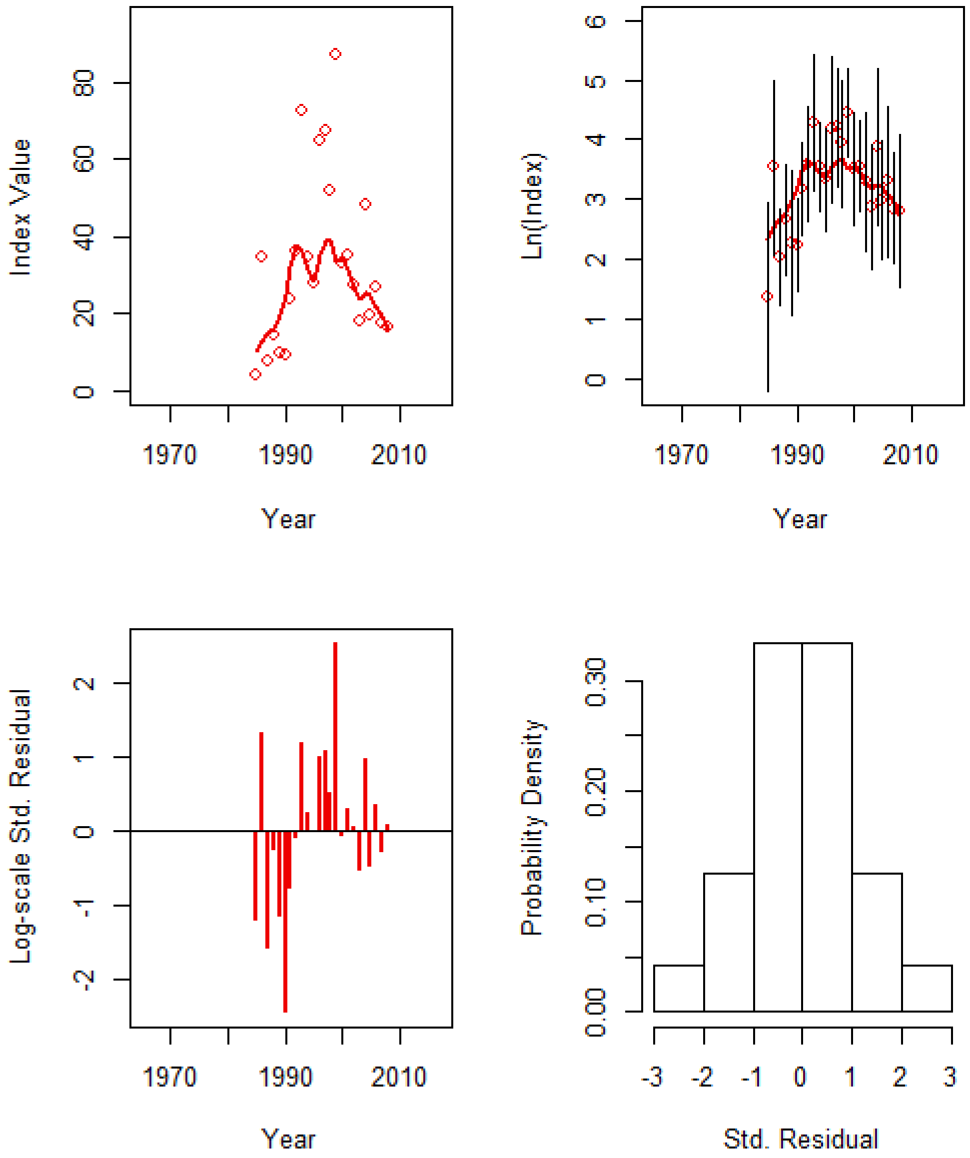


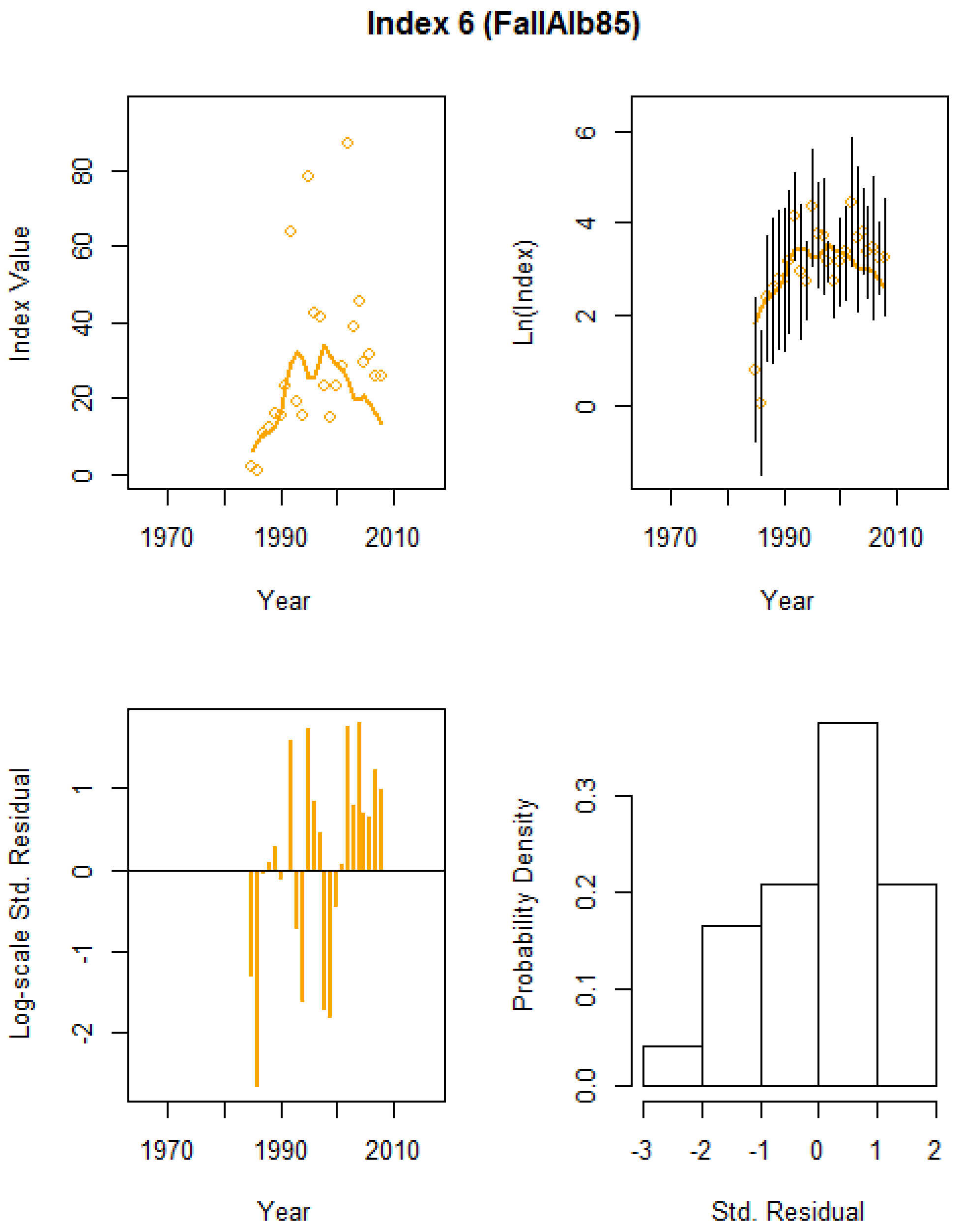

Index 2 (Fall84)
Index Value
0
1
2
3
4
5
6
Year
1970
1990
2010
Ln(Index)
-6
-4
-2
0
2
4
Log-scale Std. Residual
-3
-2
-1
0
1
2
3
Probability Density
0.00
0.05
0.10
0.15
0.20
0.25
Std. Residual
-3
-1
0
1
2
3
4

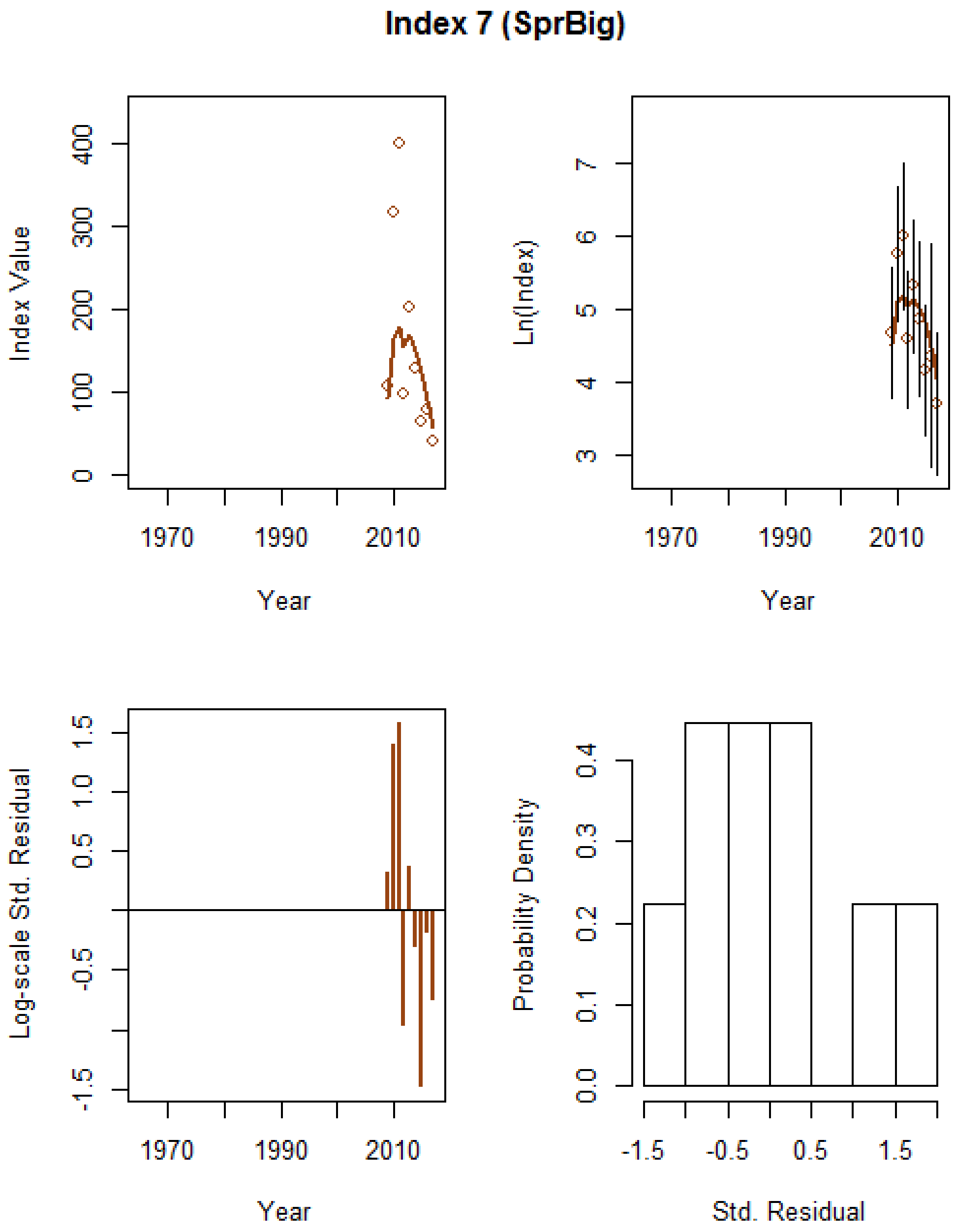

Index 3 (Shrimp)
Index Value
0
20
40
60
80
1970
1990
2010
Year
Ln(Index)
-2
0
2
4
6
1970
1990
2010
Year
Log-scale Std. Residual
-3
-2
-1
0
1
2
3
1970
1990
2010
Year
Probability Density
0.0
0.1
0.2
0.3
-4
-2
0
1
2
3
Std. Residual


Index 4 (Acoust)
Index Value
0
50
100
150
200
1970
1990
2010
Year
Ln(Index)
3
4
5
6
7
1970
1990
2010
Year
Log-scale Std. Residual
-3
-2
-1
0
1
2
3
1970
1990
2010
Year
Probability Density
0.00
0.05
0.10
0.15
0.20
-4
-2
0
1
2
3
Std. Residual

Index 5 (SprAlb85)




Index 6 (FallAlb85)
Index Value
0
20
40
60
80
1970
1990
2010
Year
Ln(Index)
0
2
4
6
1970
1990
2010
Year
Log-scale Std. Residual
-2
-1
0
1
1970
1990
2010
Year
Probability Density
0.0
0.1
0.2
0.3
-3
-2
-1
0
1
2
Std. Residual


Index 7 (SprBig)
Index Value
0
100
200
300
400
1970
1990
2010
Year
Ln(Index)
3
4
5
6
7
Log-scale Std. Residual
-1.5
-0.5
0.5
1.0
1.5
Probability Density
0.0
0.1
0.2
0.3
0.4
-1.5
-0.5
0.5
1.5
Std. Residual

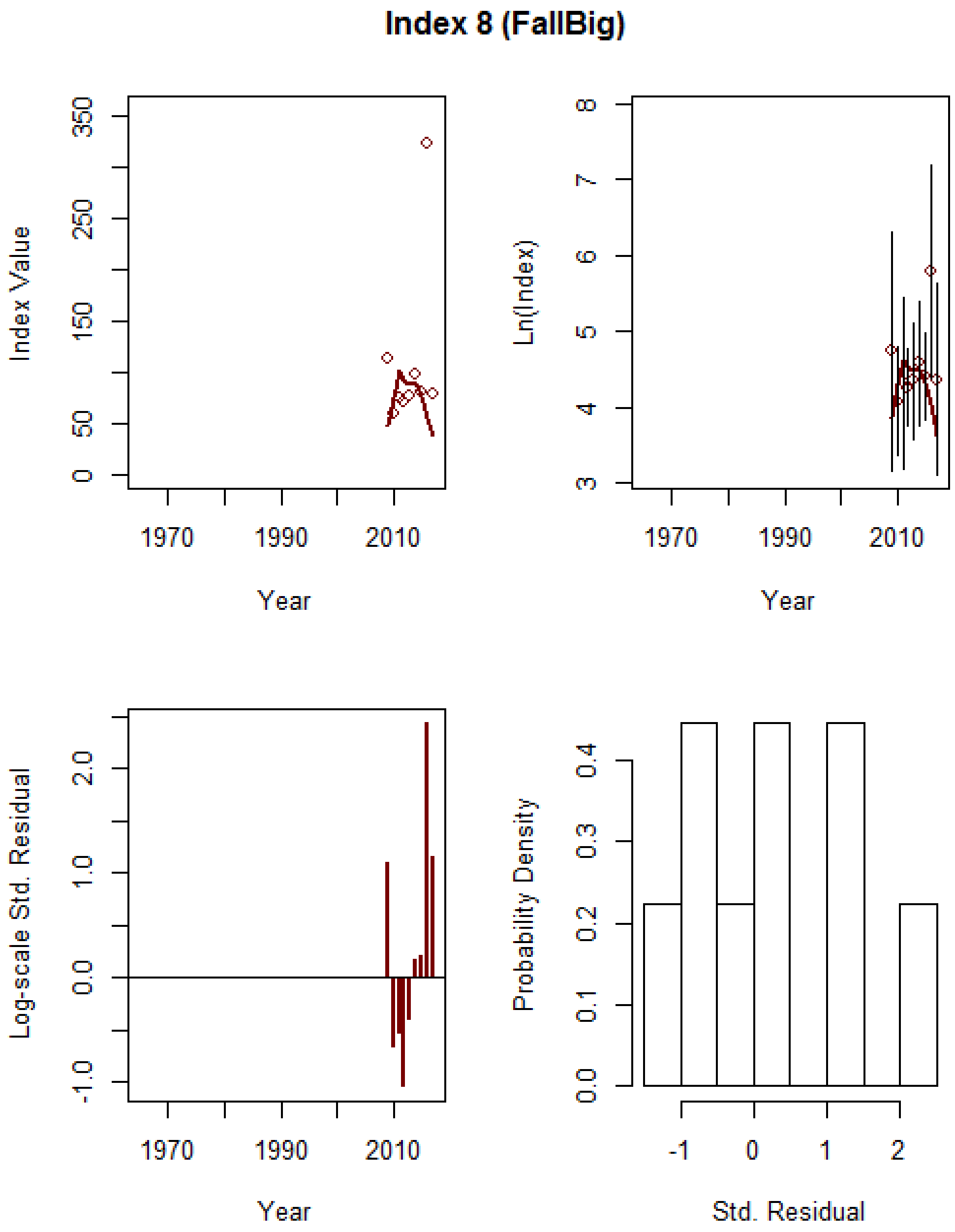
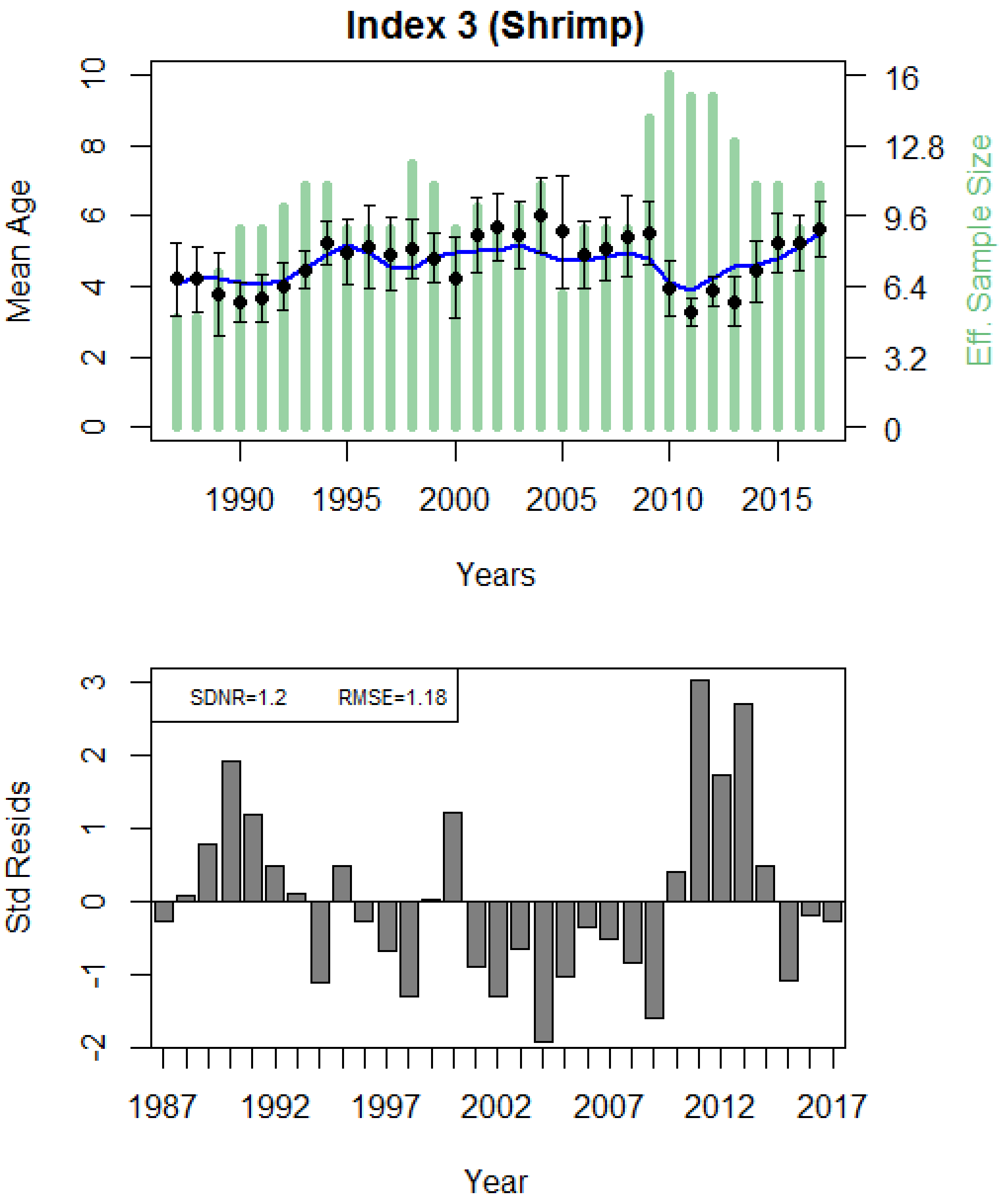
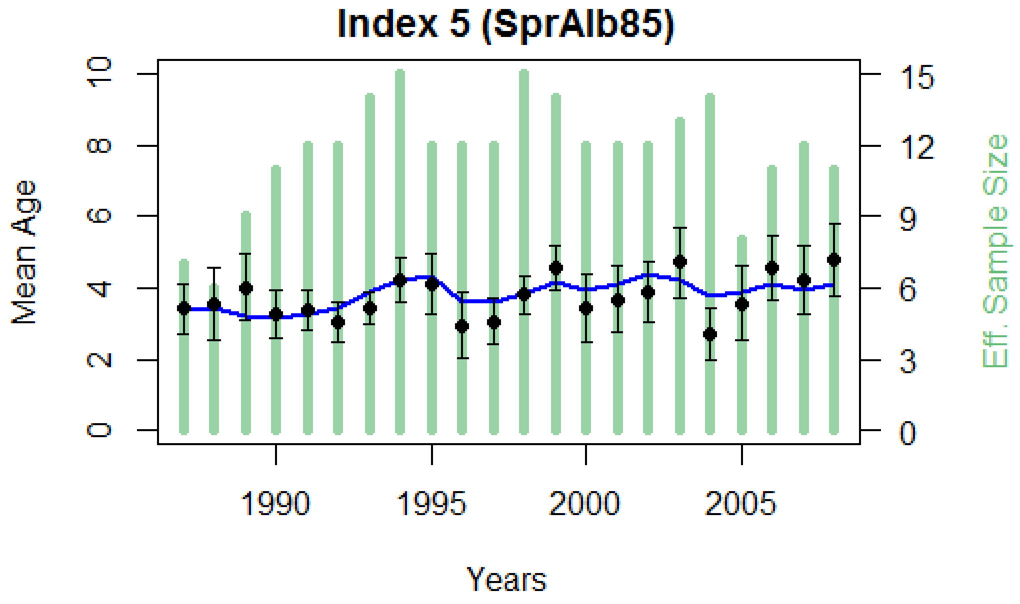
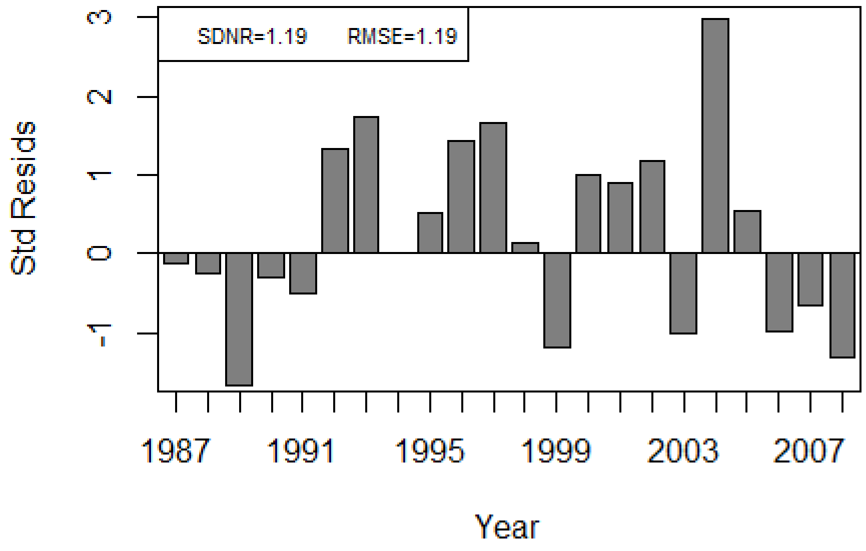
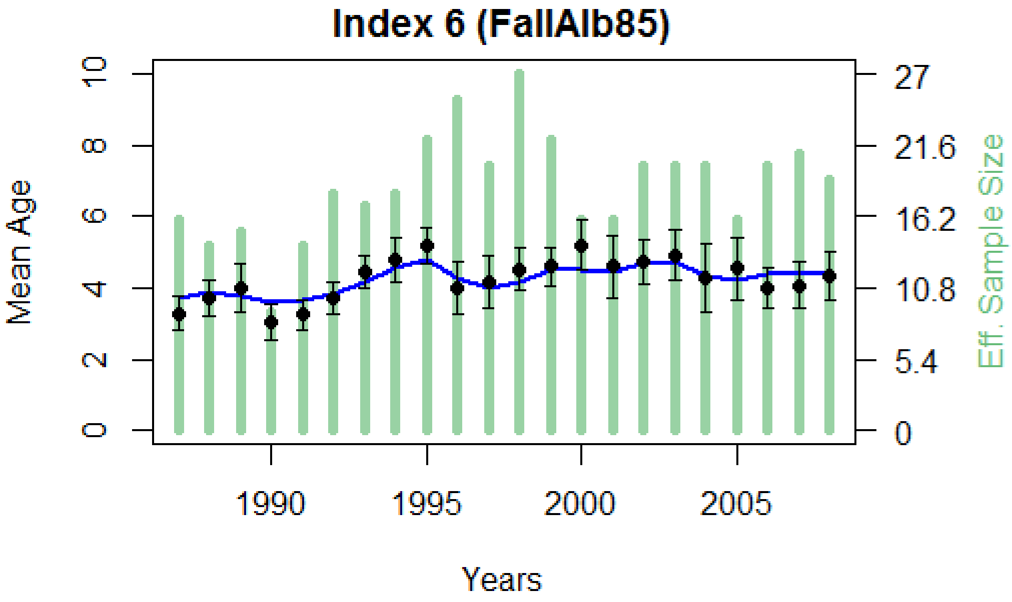

Index 8 (FallBig)

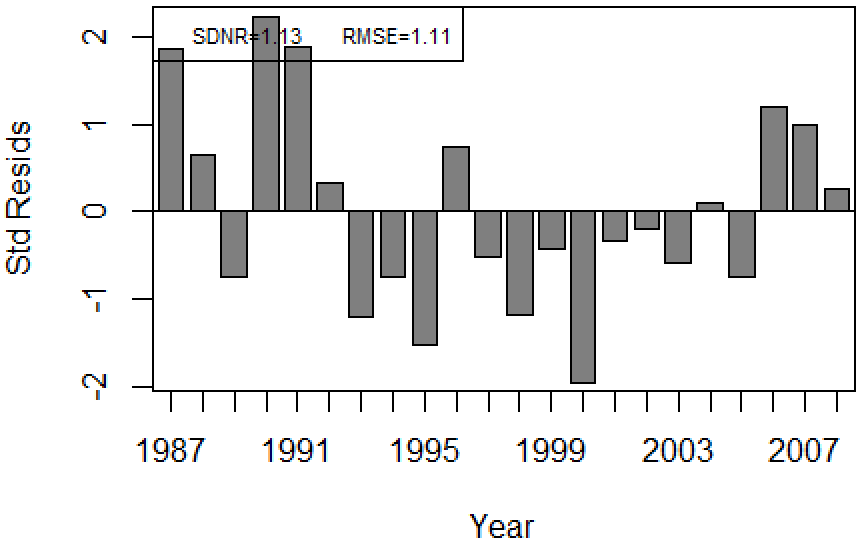
Figure B4- 15 Fits to Atlantic herring mean age for the base ASAP model (Shrimp: NMFS summer/shrimp; Spr85: Albatross 1985-2008; Fall85: Albatross 1985-2008; SprBig: Bigelow 2009-2017; FallBig: Bigelow 2009-2017)

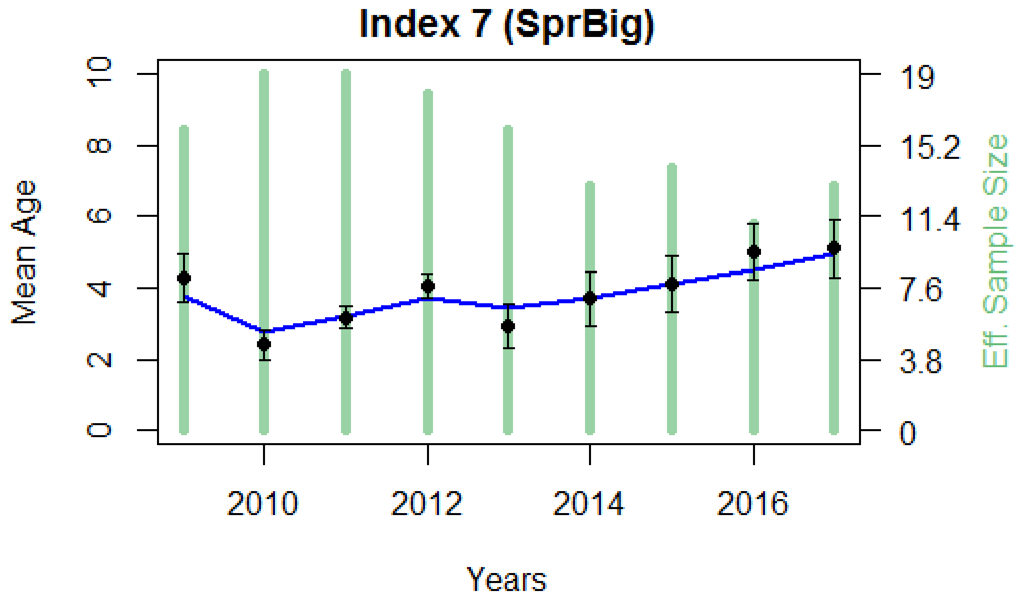


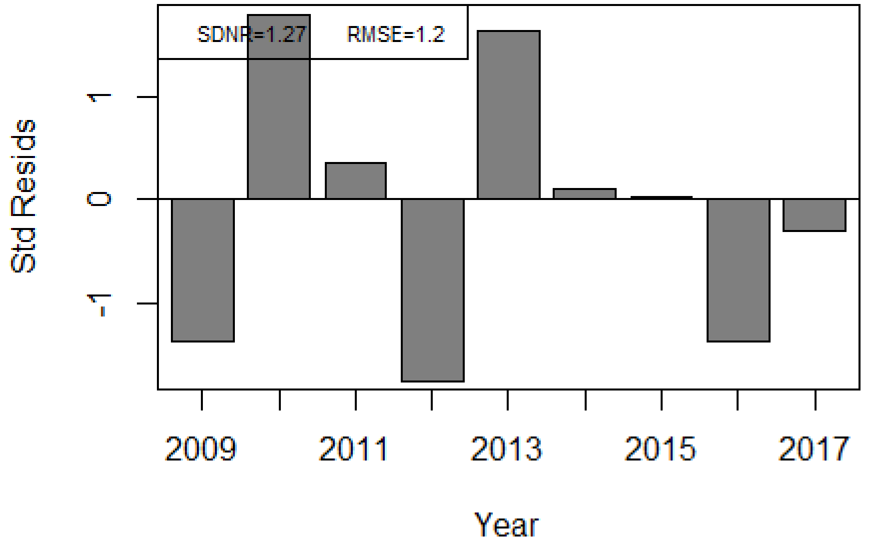

Index 5 (SprAlb85)
Mean Age
0
2
4
6
8
10
Eff. Sample Size
0
3
6
9
12
15
1990
1995
2000
2005
Years

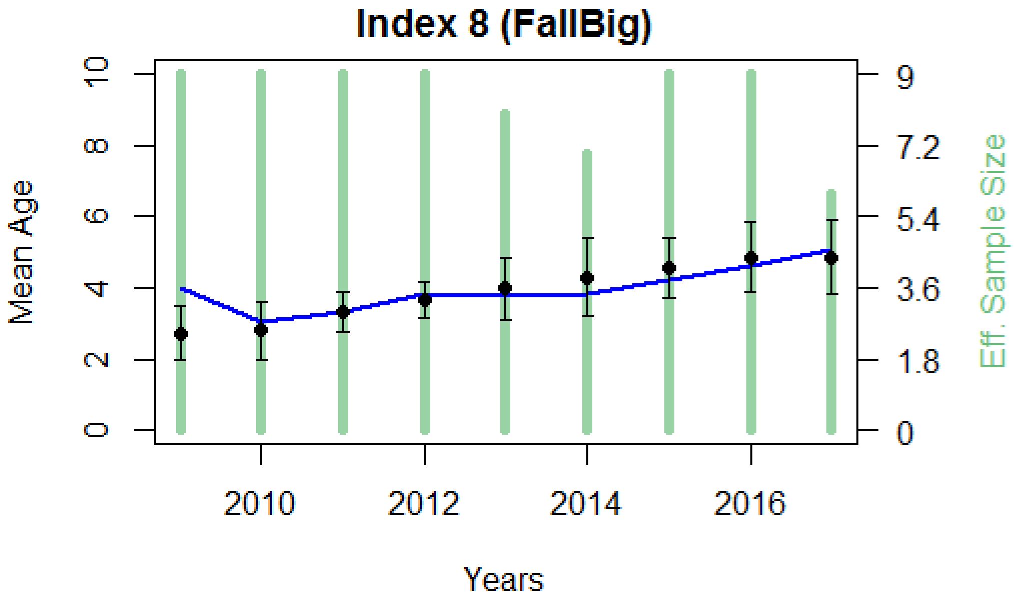

SDNR=1.19
RMSE=1.19
Std Resids
-1
0
1
2
3
1987
1991
1995
1999
2003
2007
Year


Index 6 (FallAlb85)
Mean Age
0
2
4
6
8
10
Eff. Sample Size
0
5.4
10.8
16.2
21.6
27
1990
1995
2000
2005
Years


SDNR=1.13
RMSE=1.11
Std Resids
-2
-1
0
1
2
1987
1991
1995
1999
2003
2007
Year


Index 7 (SprBig)
Mean Age
0
2
4
6
8
10
19
15.2
11.4
7.6
3.8
0
Eff. Sample Size
2010
2012
2014
2016
Years


SDNR=1.27
RMSE=1.2
Std Resids
1
0
-1
2009
2011
2013
2015
2017
Year


Index 8 (FallBig)
Mean Age
0
2
4
6
8
10
Eff. Sample Size
0
1.8
3.6
5.4
7.2
9
2010
2012
2014
2016
Years

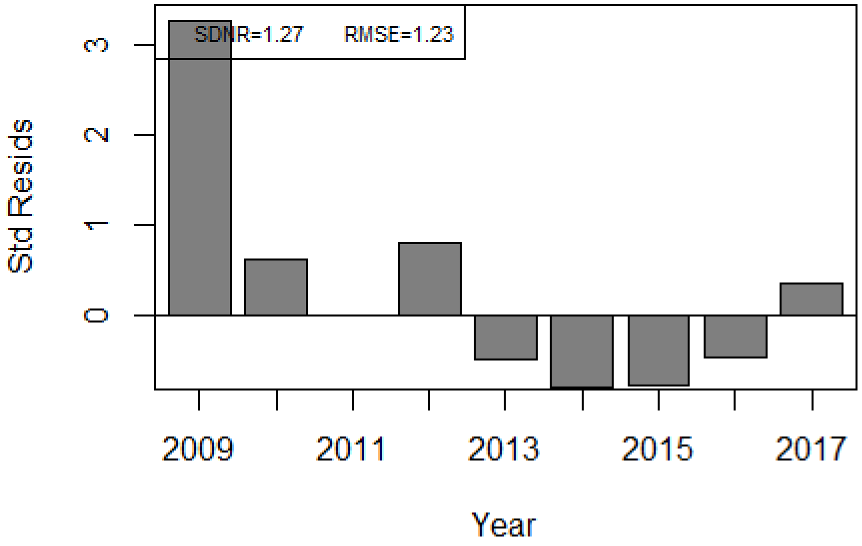
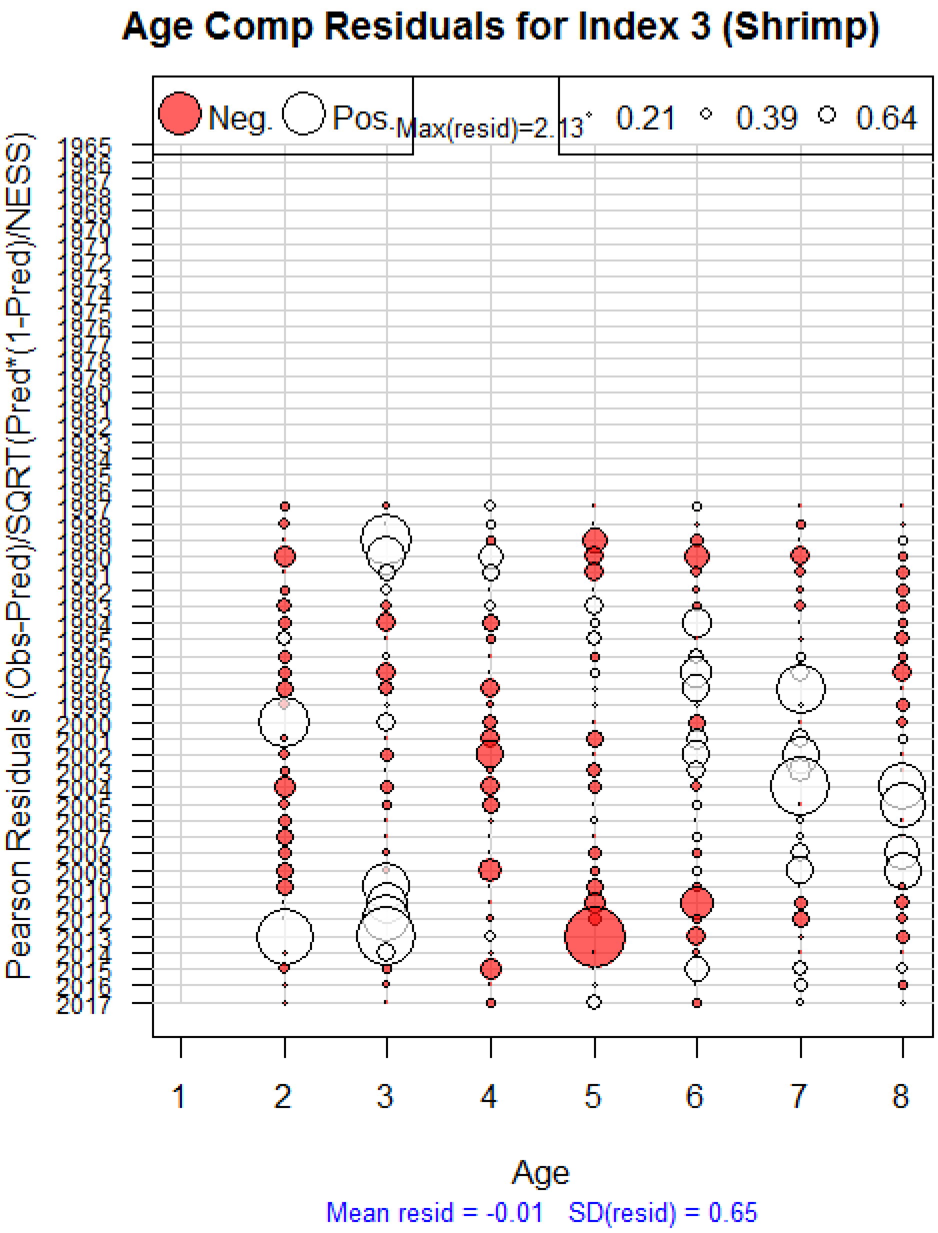
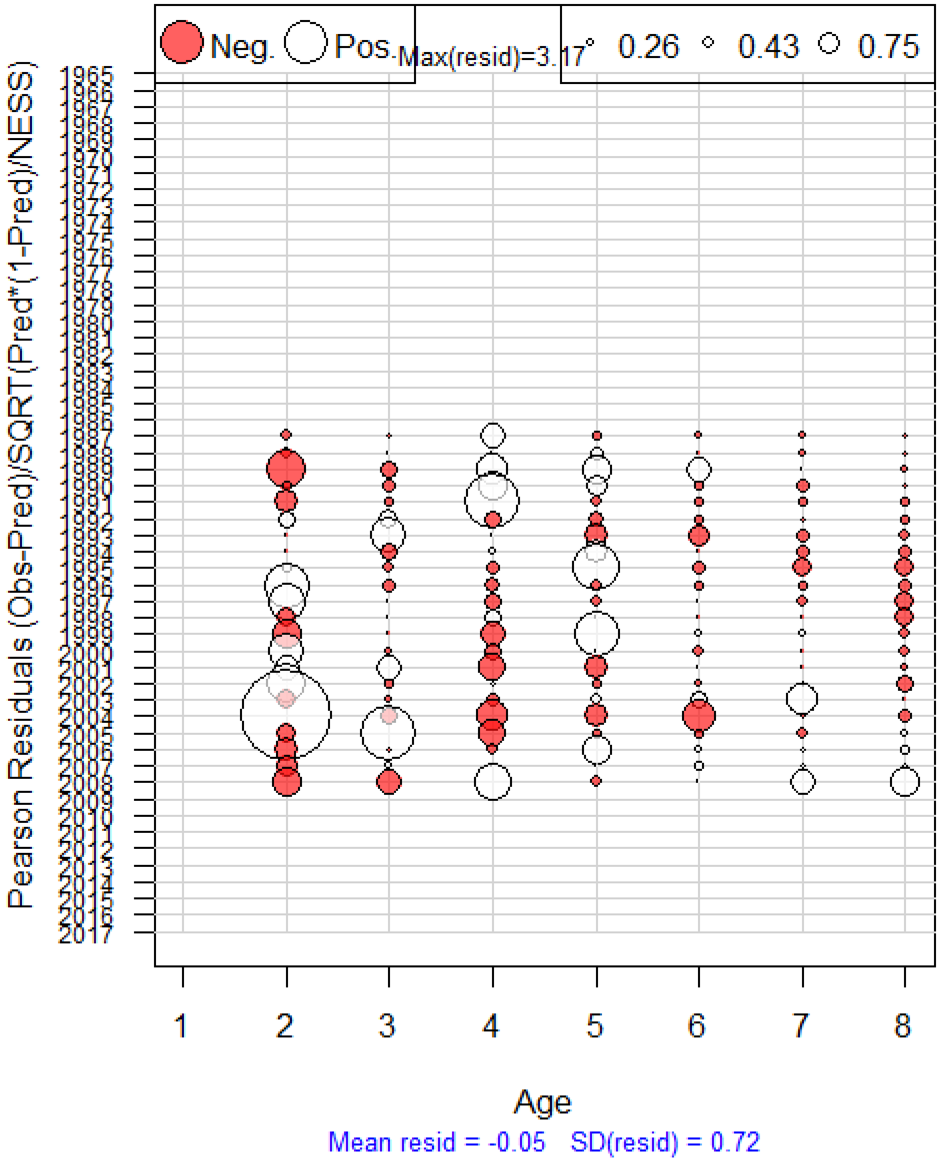
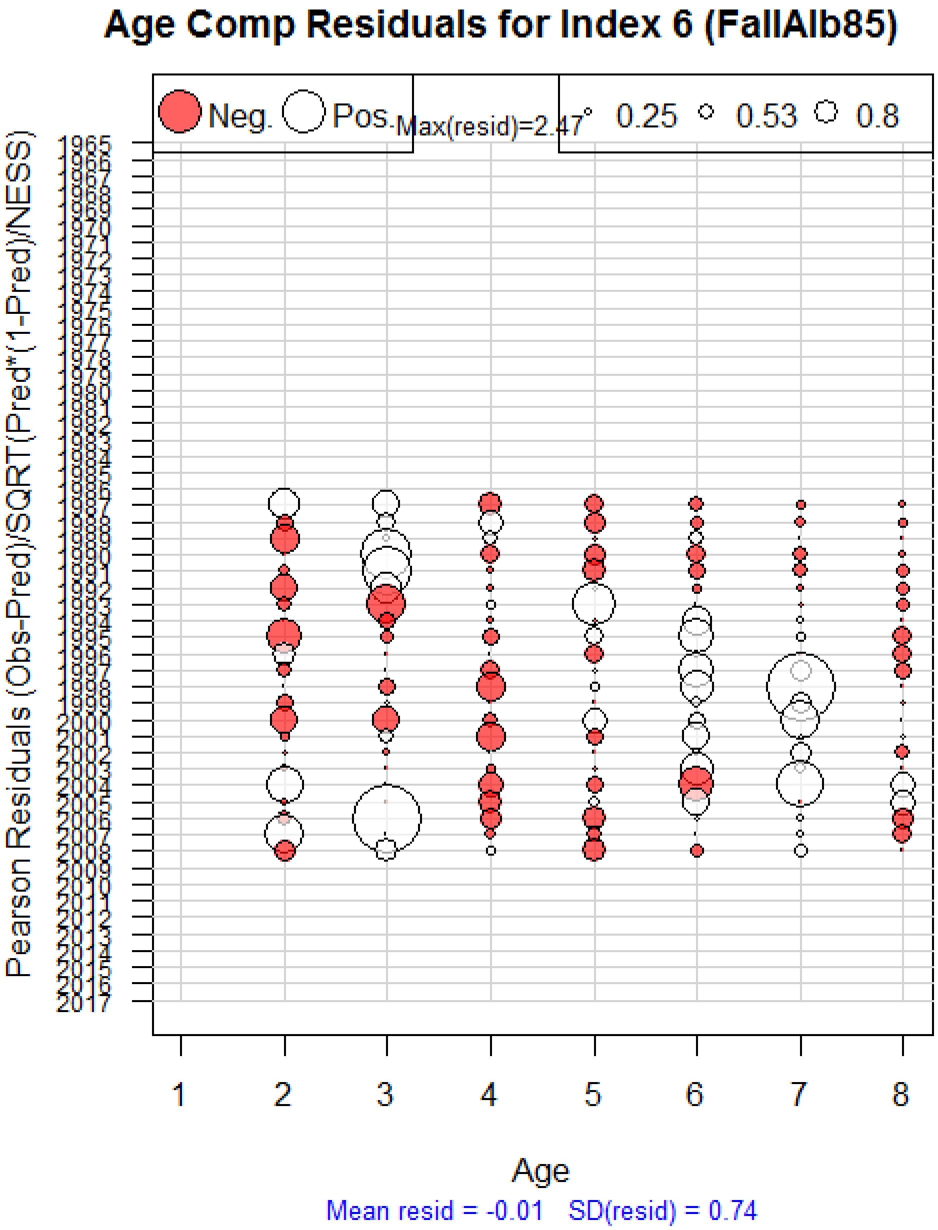

SDNR=1.27
RMSE=1.23
Std Resids
0
1
2
3
2009
2011
2013
2015
2017
Year

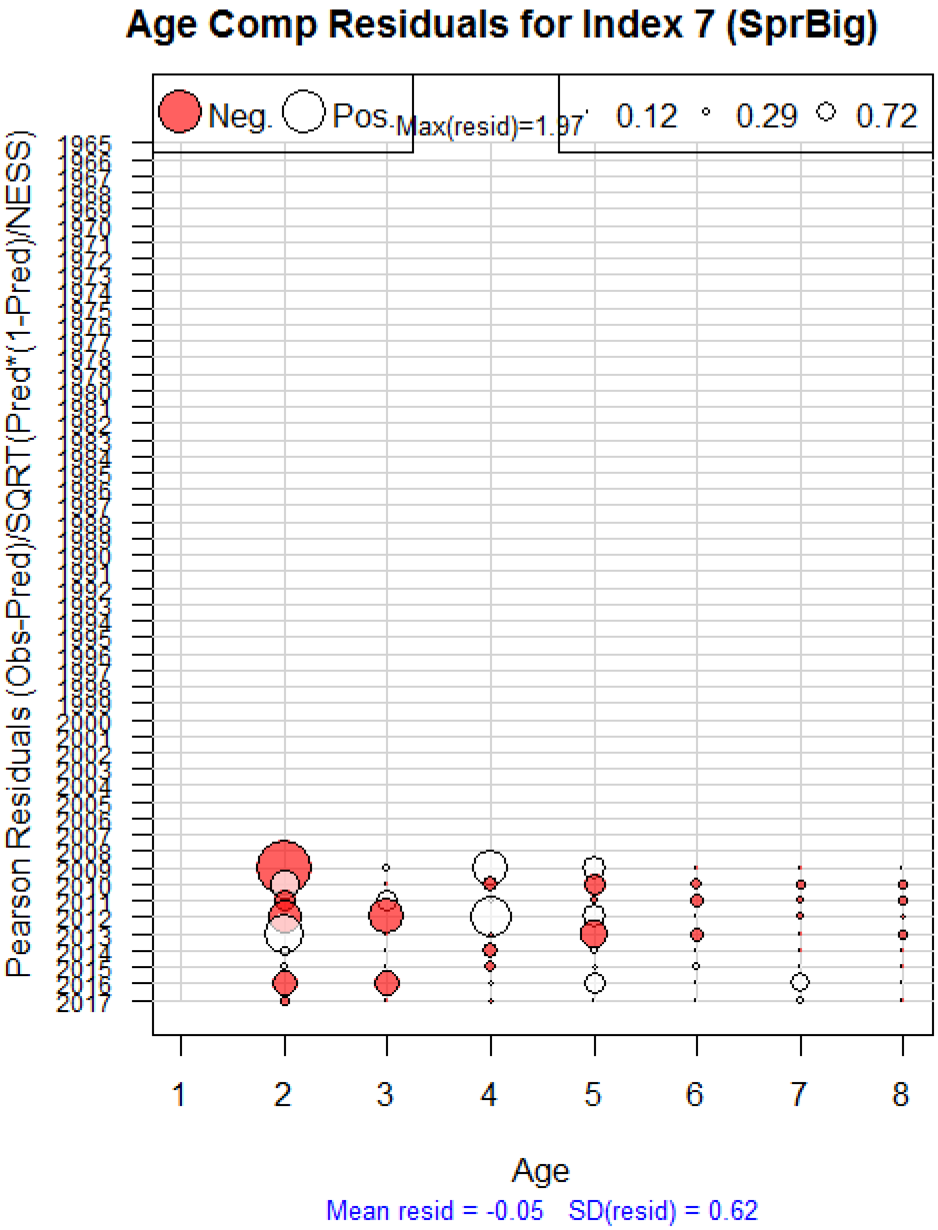
Figure B4- 16 Fits to Atlantic herring age compositions for the base ASAP model (Shrimp: NMFS summer/shrimp; Spr85: Albatross 1985-2008; Fall85: Albatross 1985-2008; SprBig: Bigelow 2009-2017; FallBig: Bigelow 2009-2017)



Age Comp Residuals for Index 5 (SprAlb85)




Age Comp Residuals for Index 6 (FallAlb85)
Neg.
Pos.
Max(resid)=2.47
0.25
0.53
0.8
Pearson Residuals (Obs-Pred)/SQRT(Pred*(1-Pred)/NESS)
1965
2017
1
2
3
4
5
6
7
8
Age
Mean resid = -0.01 SD(resid) = 0.74


Age Comp Residuals for Index 7 (SprBig)
Neg.
Pos.
Max(resid)=1.97
0.12
0.29
0.72
Pearson Residuals (Obs-Pred)/SQRT(Pred*(1-Pred)/NESS)
1965
2017
1
2
3
4
5
6
7
8
Age
Mean resid = -0.05   SD(resid) = 0.62

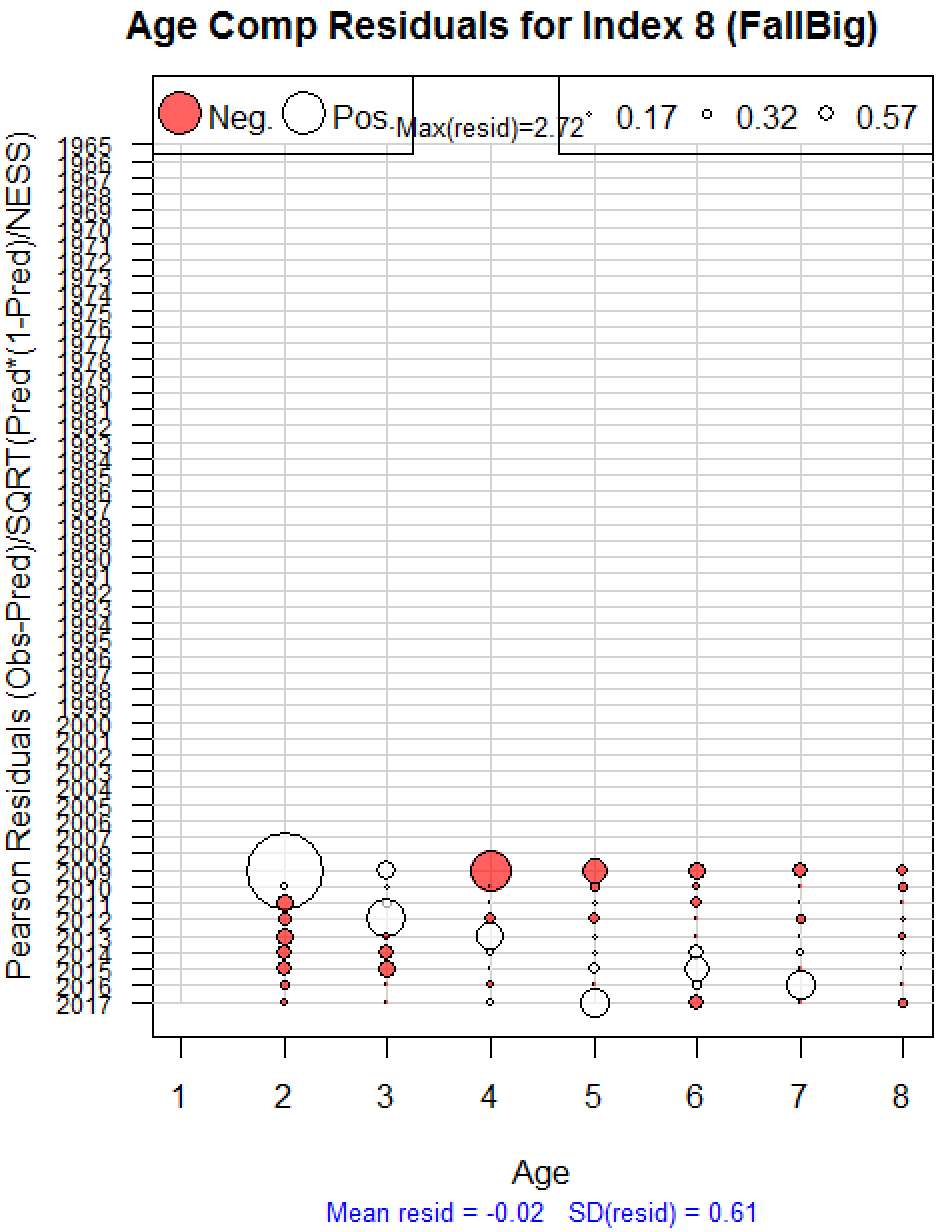

Age Comp Residuals for Index 8 (FallBig)
Neg.
Pos.
Max(resid)=2.72
0.17
0.32
0.57
Pearson Residuals (Obs-Pred)/SQRT(Pred*(1-Pred)/NESS)
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
1
2
3
4
5
6
7
8
Age
Mean resid = -0.02
SD(resid) = 0.61

Figure B4- 17 Atlantic herring catchability estimates for the indices from the base ASAP model

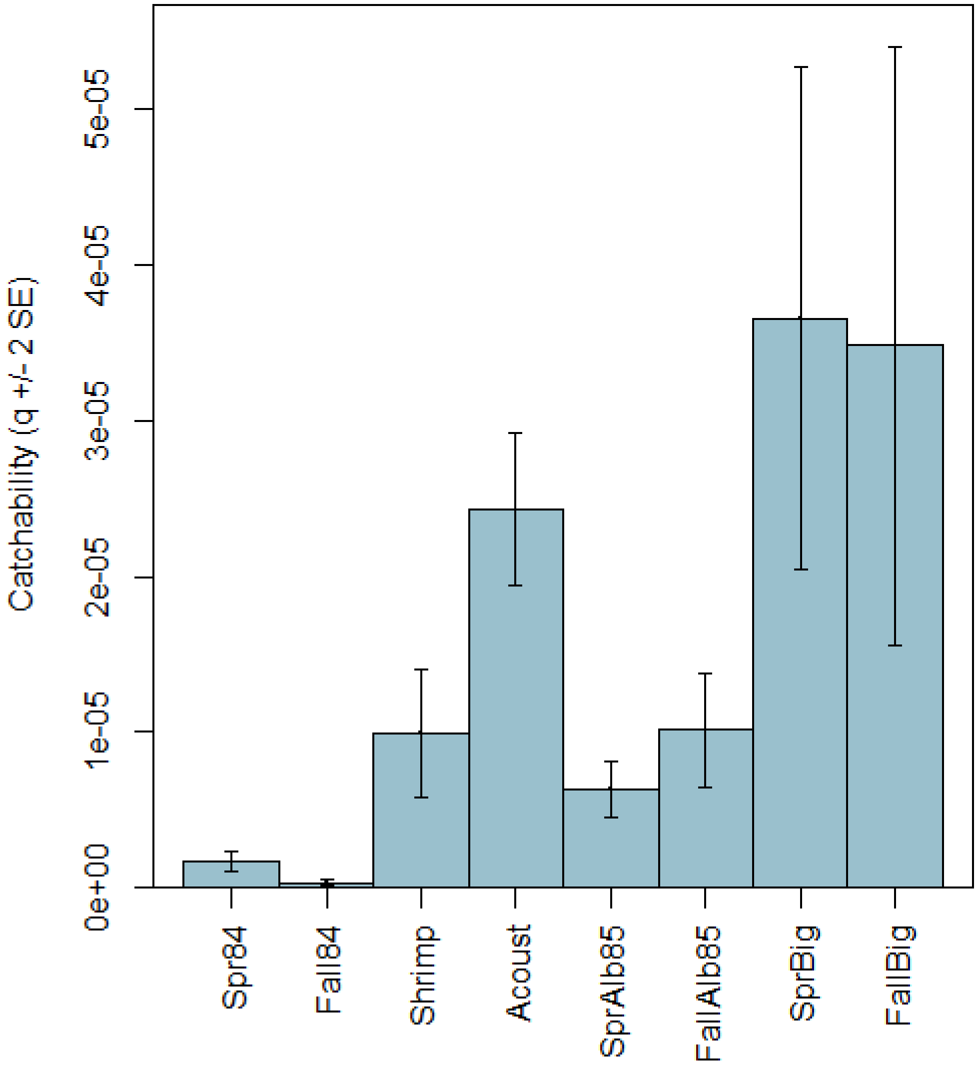


Figure B4- 18 Relative retrospective pattern for Atlantic herring SSB using a 17-year peel for the base ASAP model

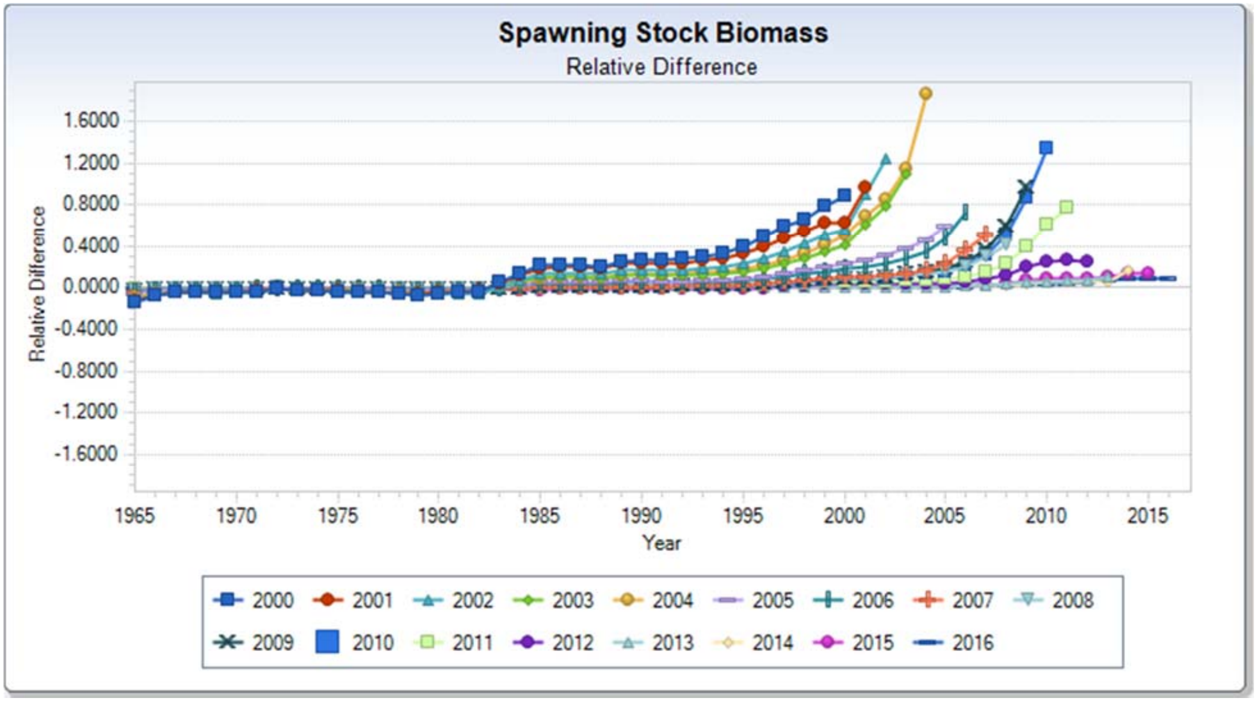


Figure B4- 19 Coefficients of variation of the time series estimates of Atlantic herring recruitment (Recr.), SSB, and F (average F over ages 7 and8) from the base ASAP model

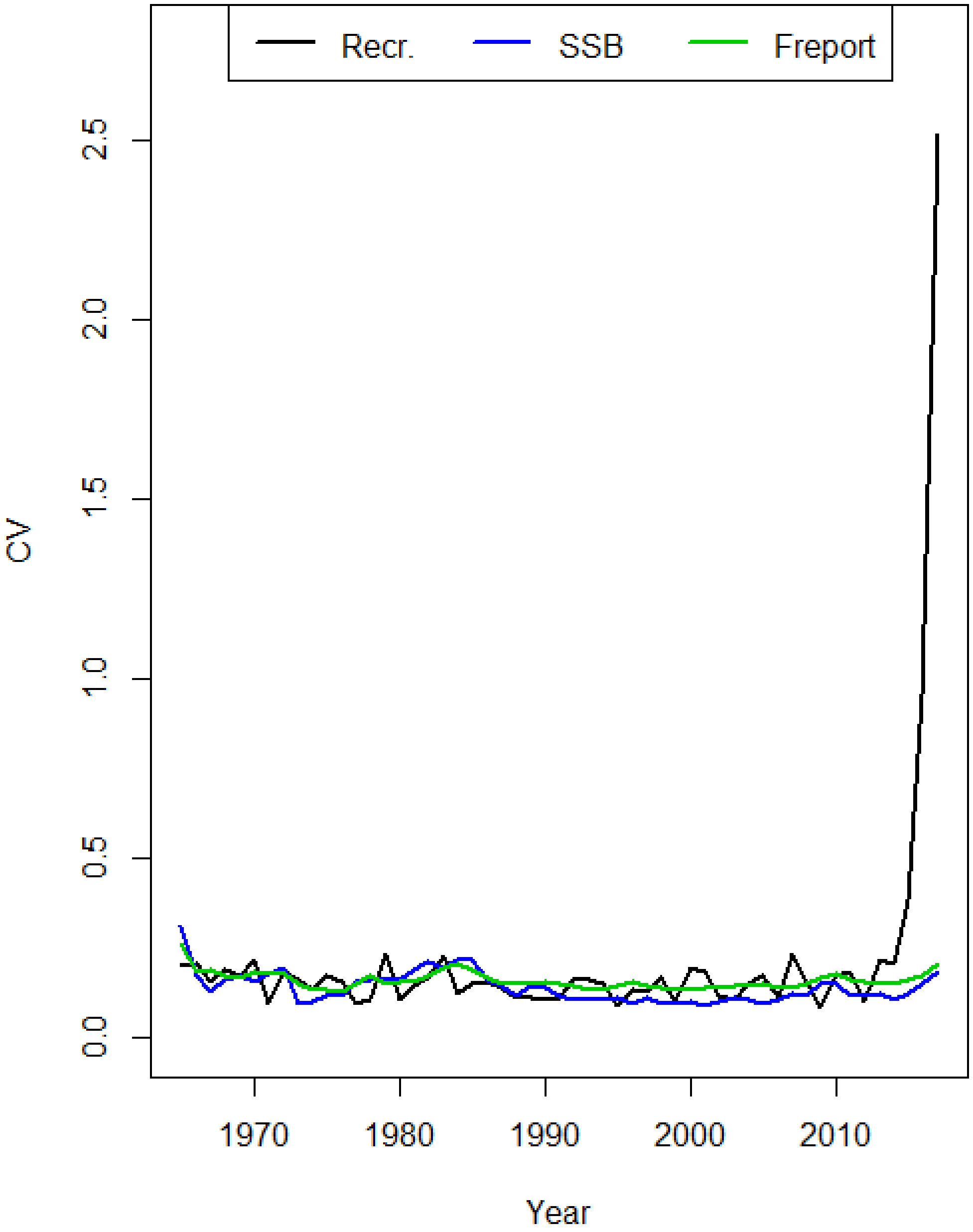


Figure B4- 20 Atlantic herring biomass time series from base ASAP model

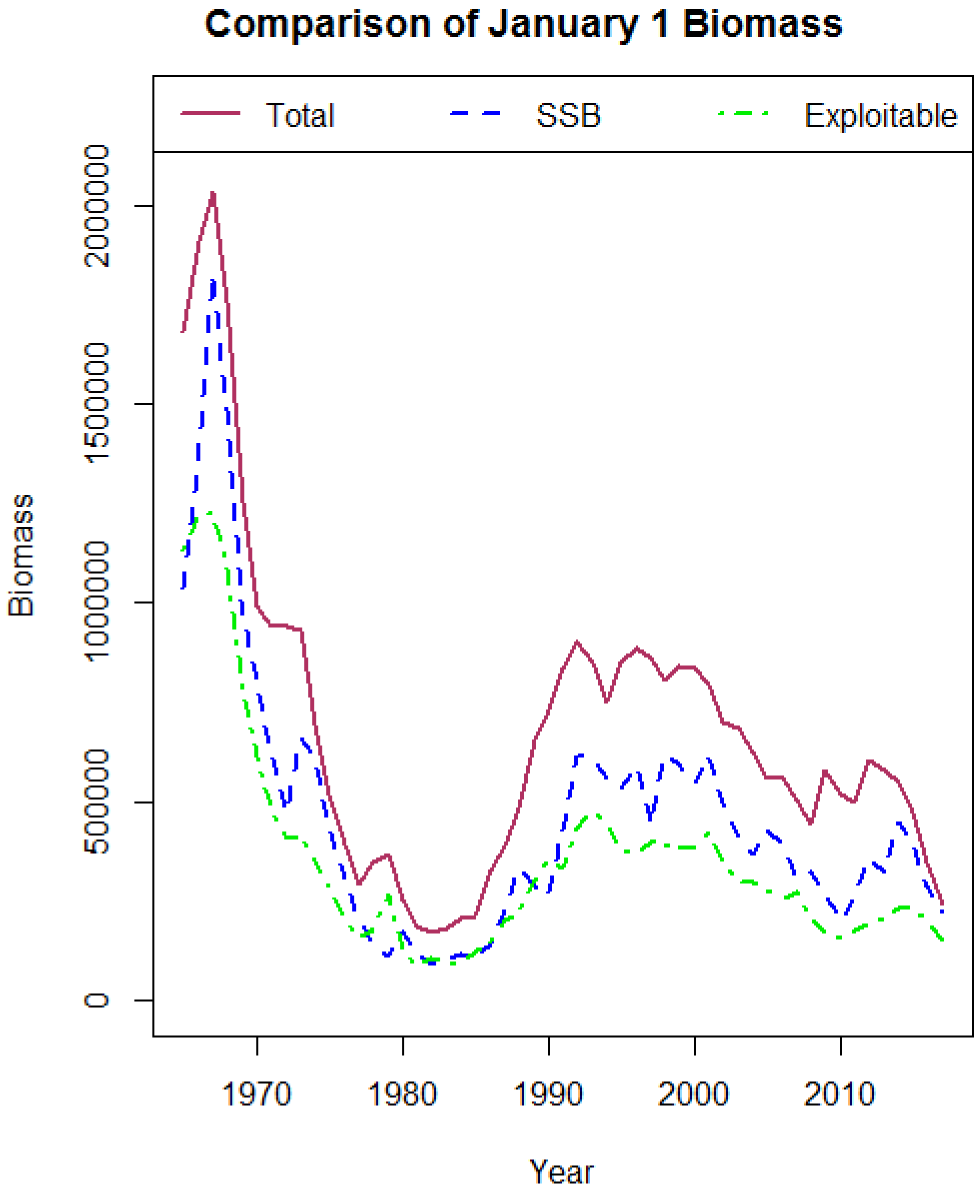


Figure B4- 21 Atlantic herring recruit time series and log-scale deviations from the base ASAP model

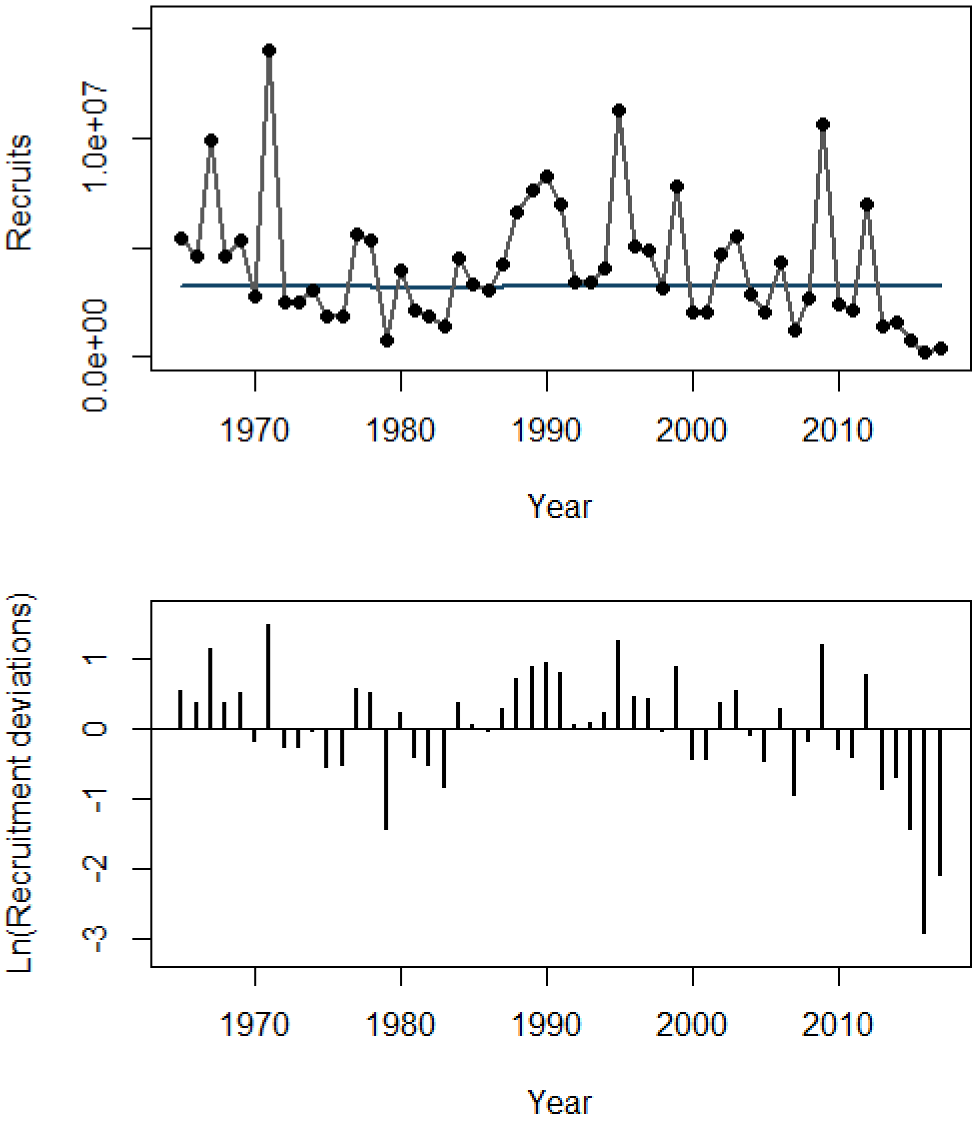


Figure B4- 22 Atlantic herring stock-recruit plot with year of recruitment as points from the base ASAP model

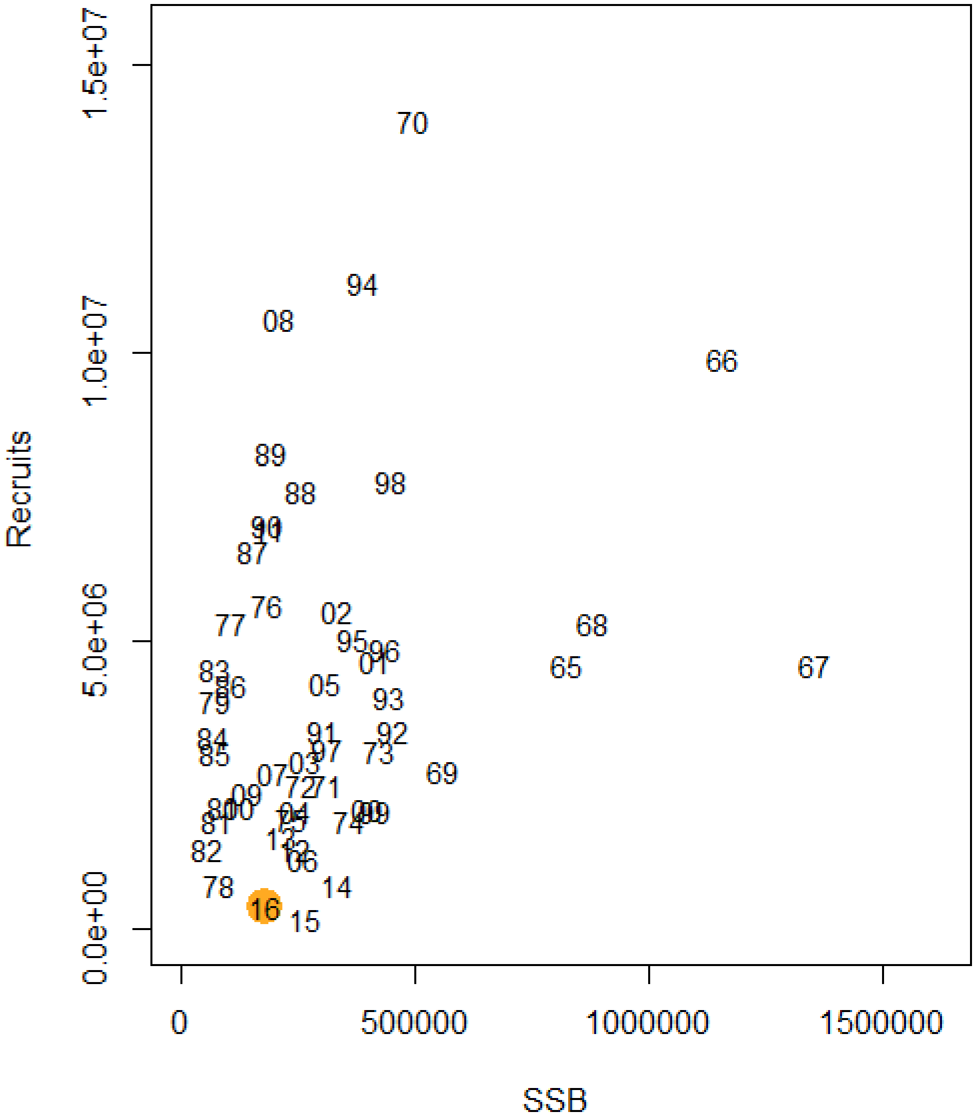


Figure B4- 23 Atlantic herring SSB, fully selected F (F.full) and average F over ages 7-8 (F.report) from the base ASAP model

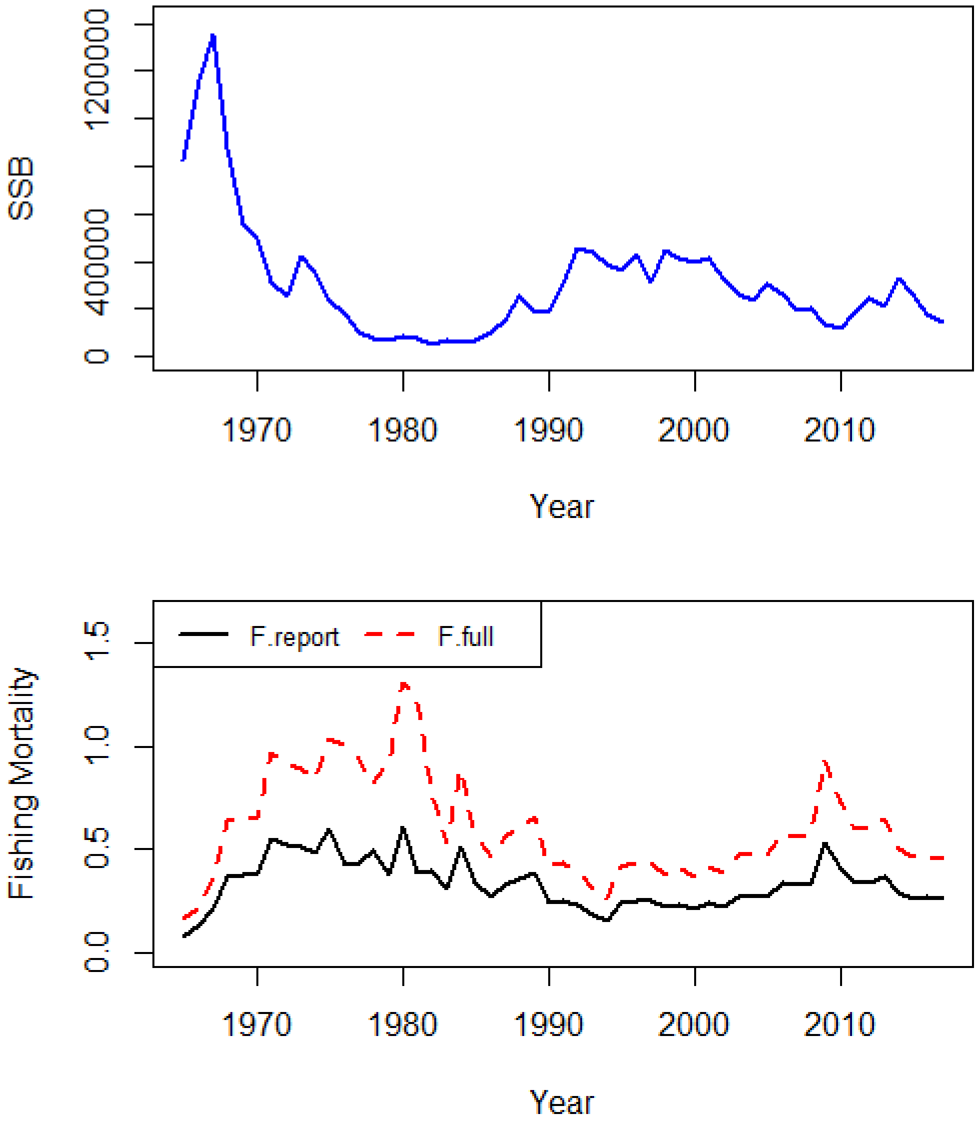
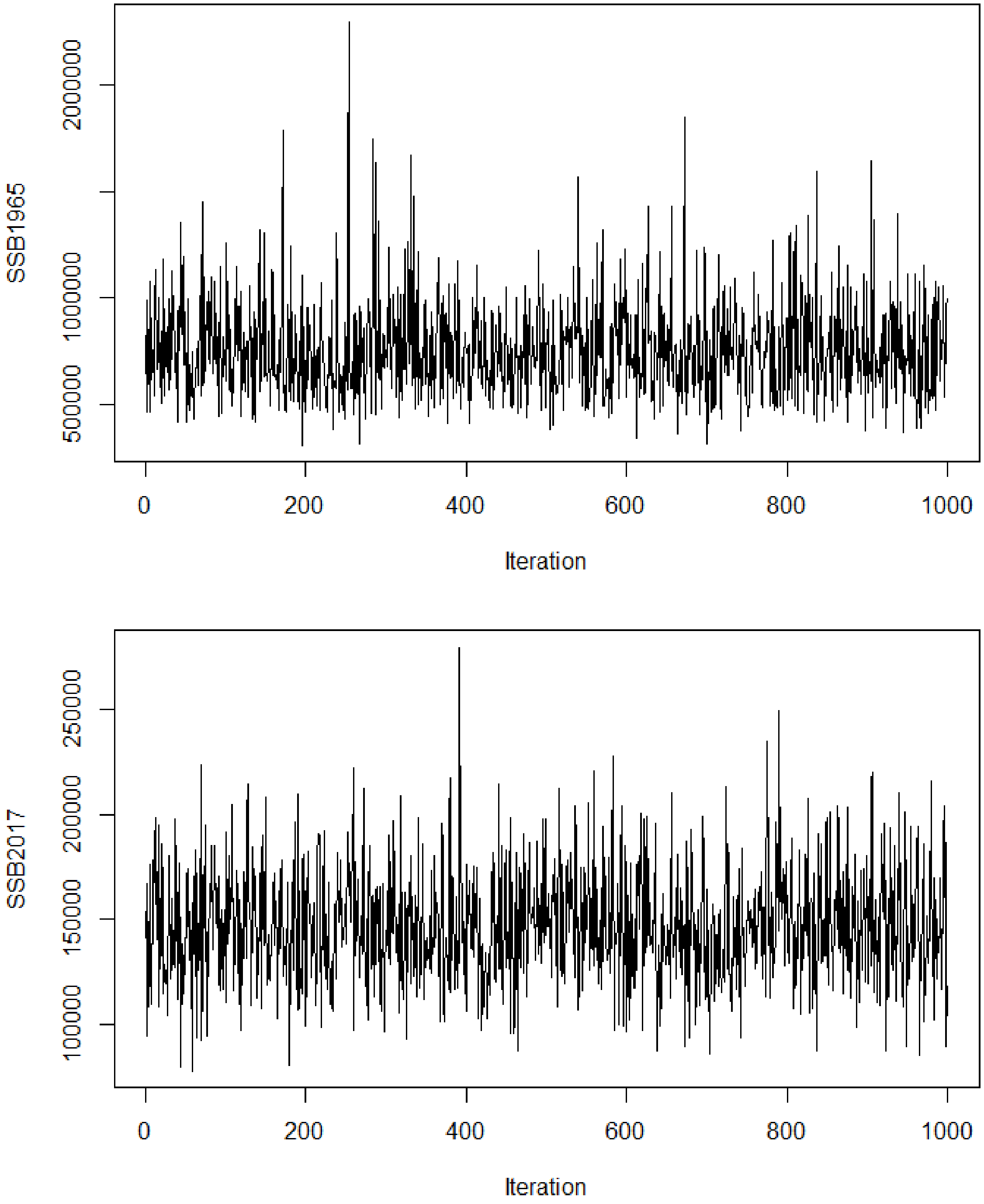
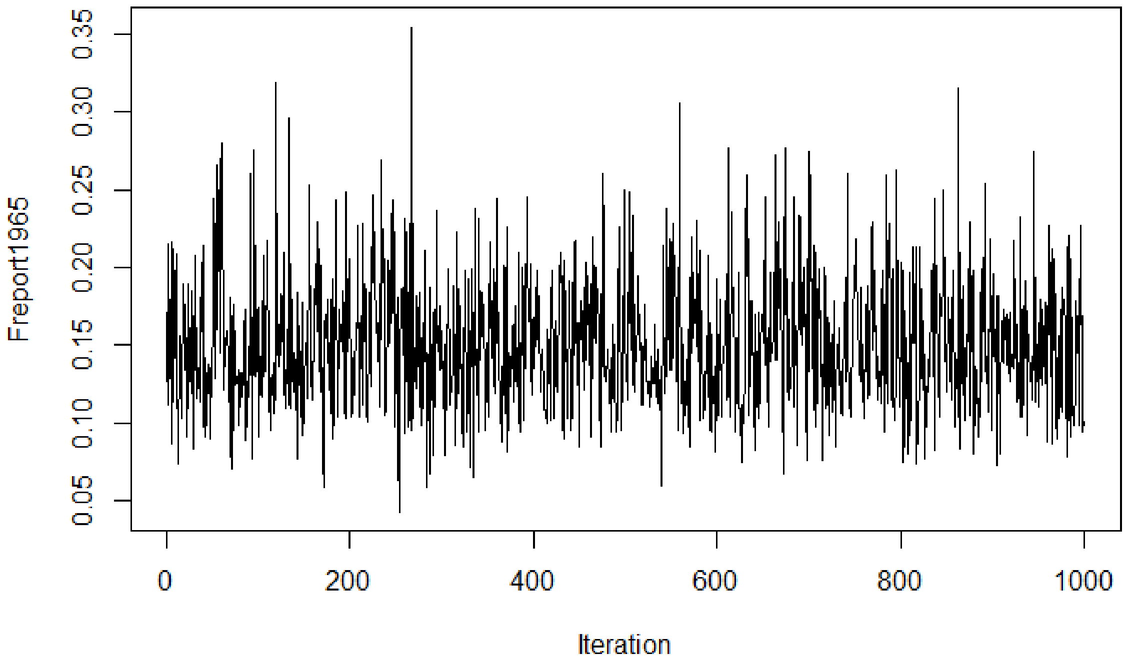
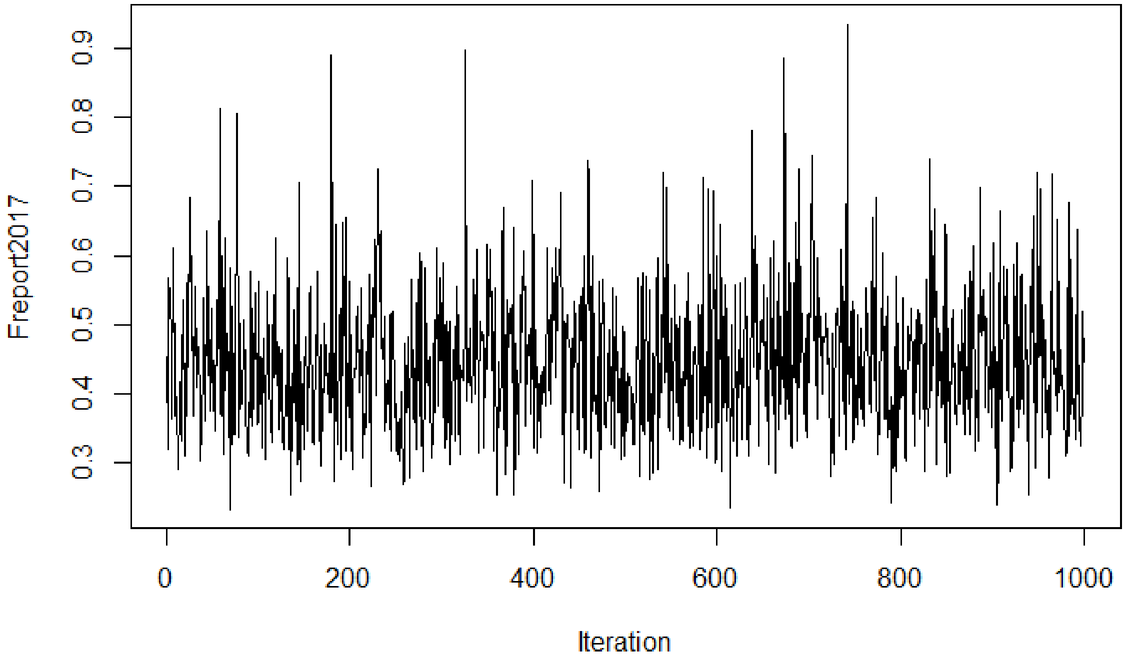


Figure B4- 24 Trace plots for SSB and F in 1965 and 2017 from MCMC of the base ASAP model



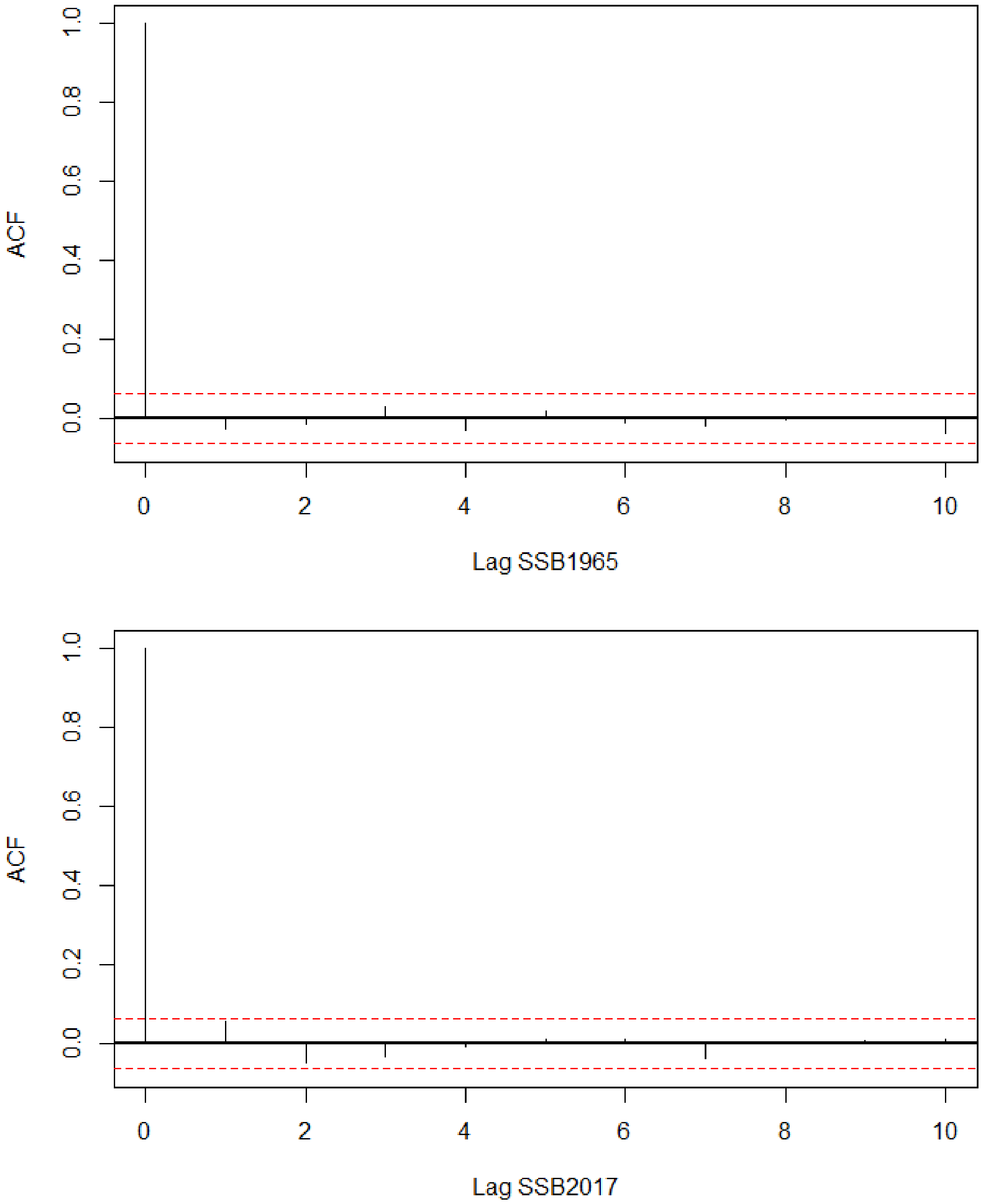


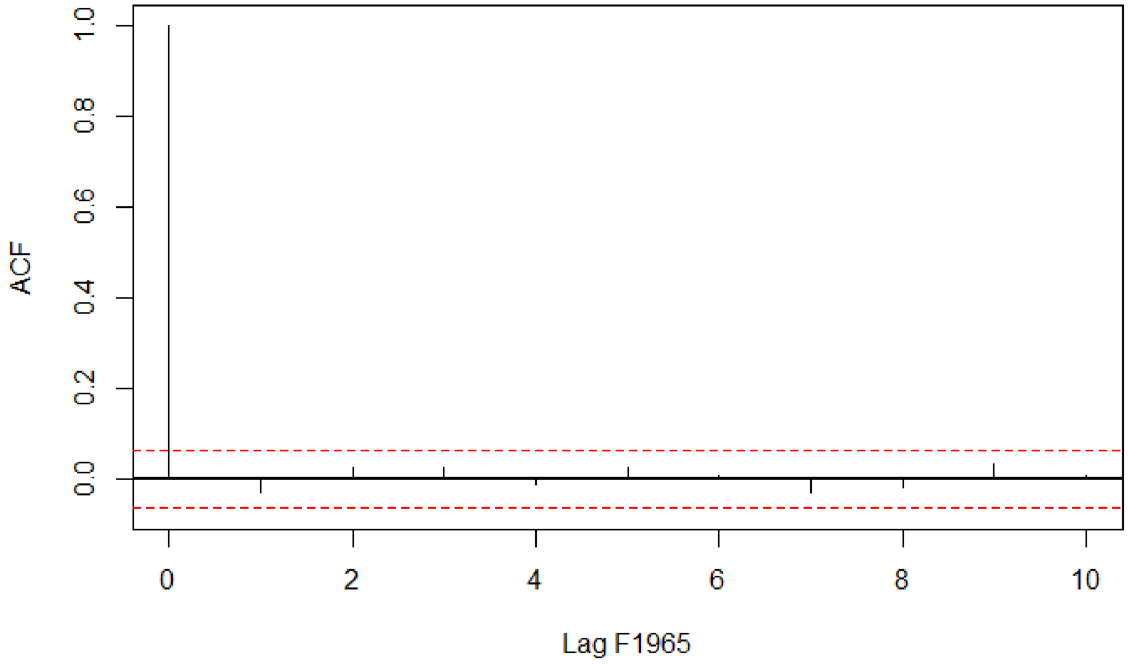
Freport1965
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
200
400
600
800
1000
Iteration



Freport2017
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
200
400
600
800
1000
Iteration

Figure B4- 25 Correlations of lags for SSB and F in 1965 and 2017 from the MCMC of the base ASAP model




ACF
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Lag F1965

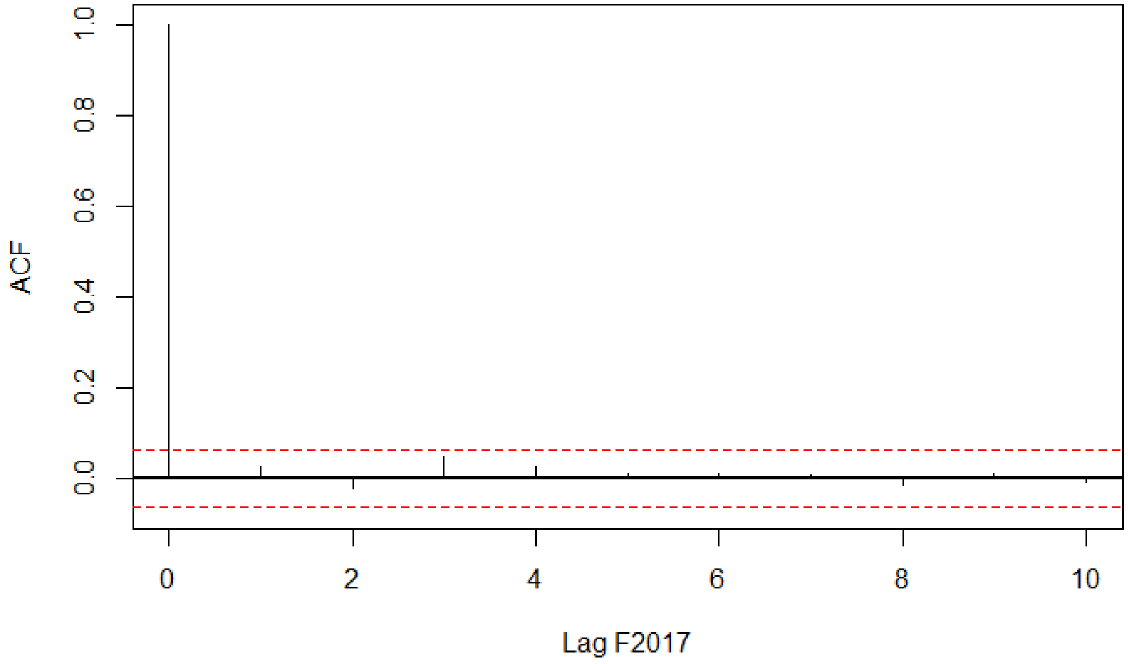
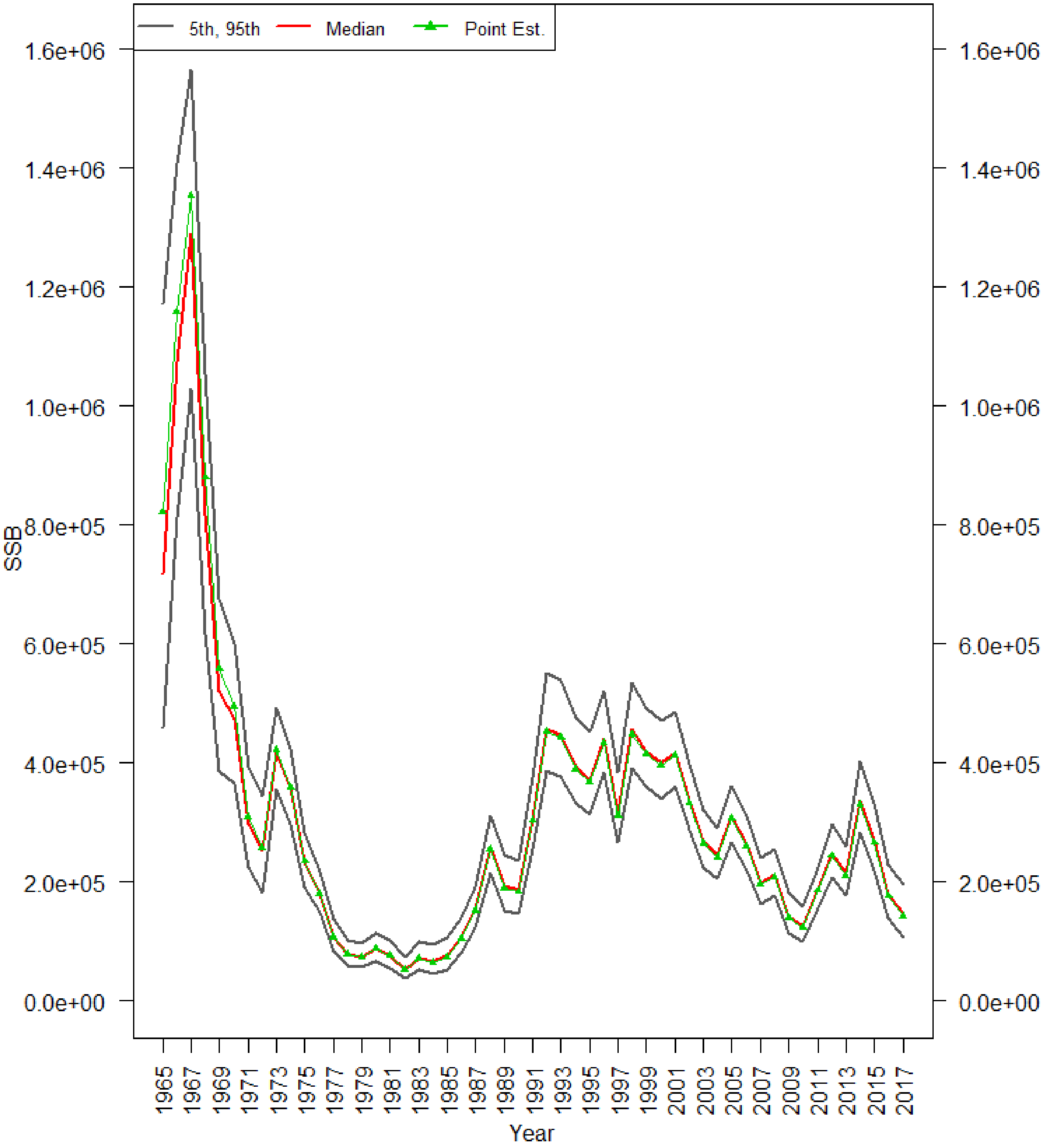

ACF
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Lag F2017

Figure B4- 26 Point estimates, median, and 90% probability intervals of Atlantic herring SSB and F from the MCMC of the base ASAP model



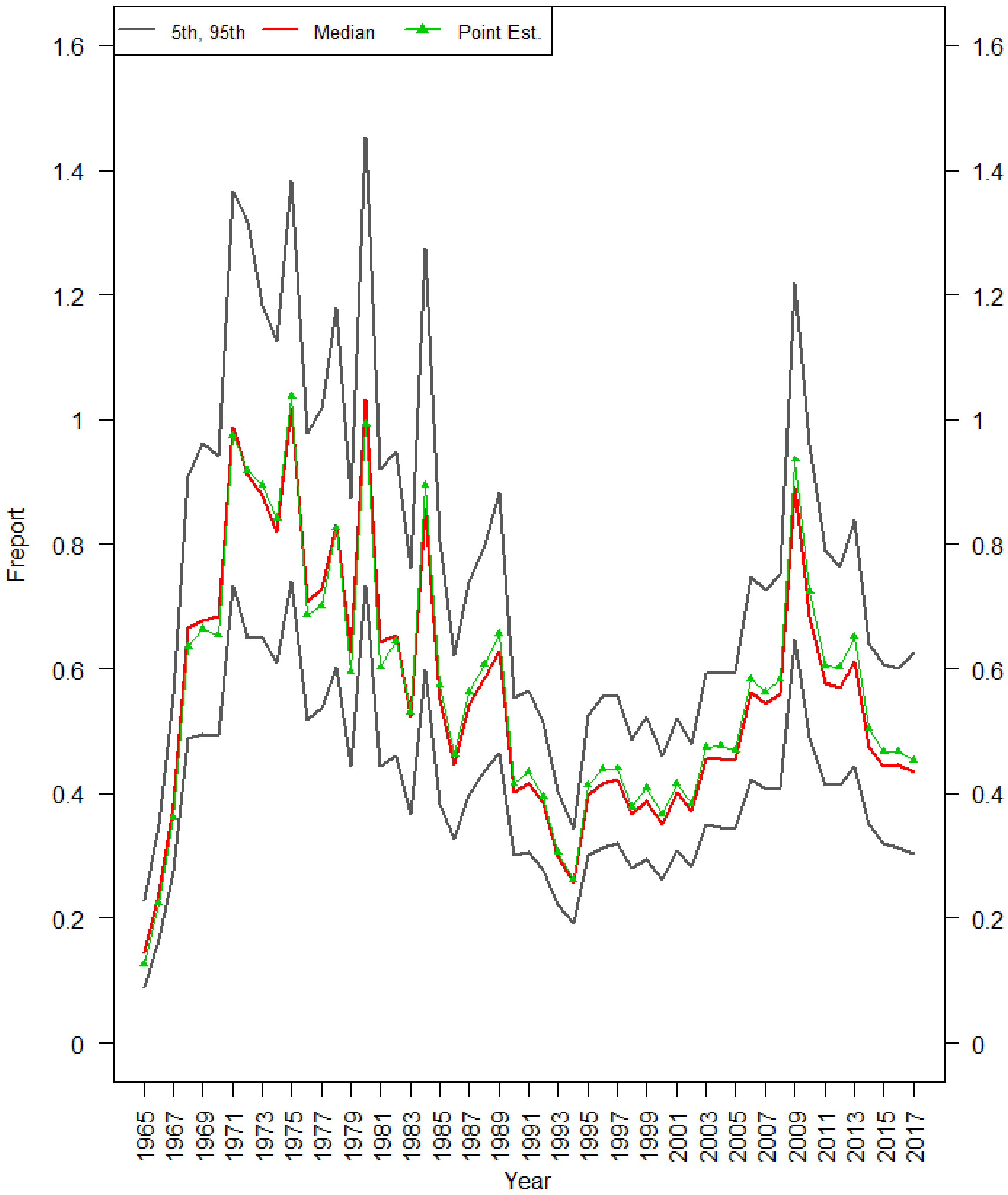
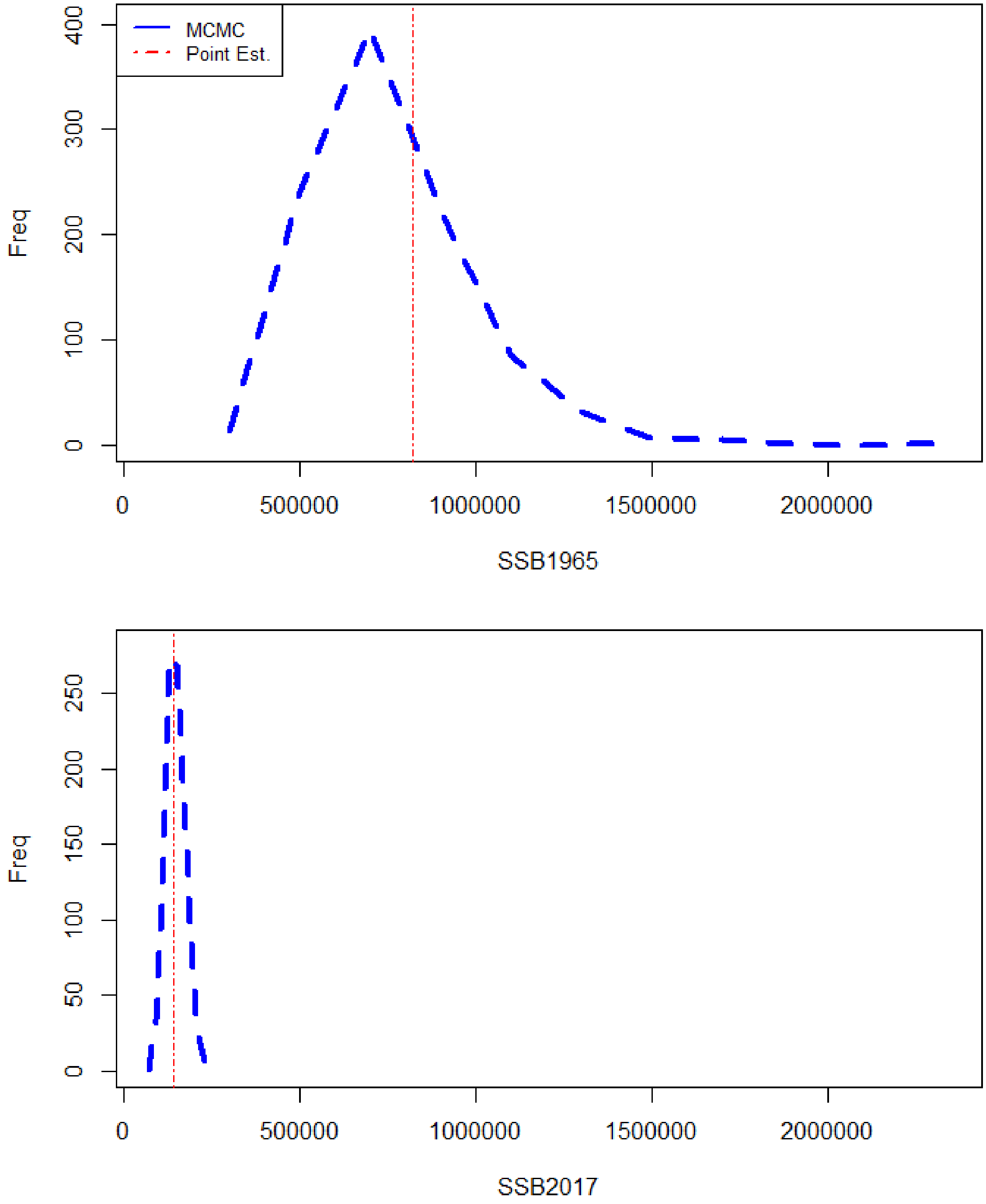
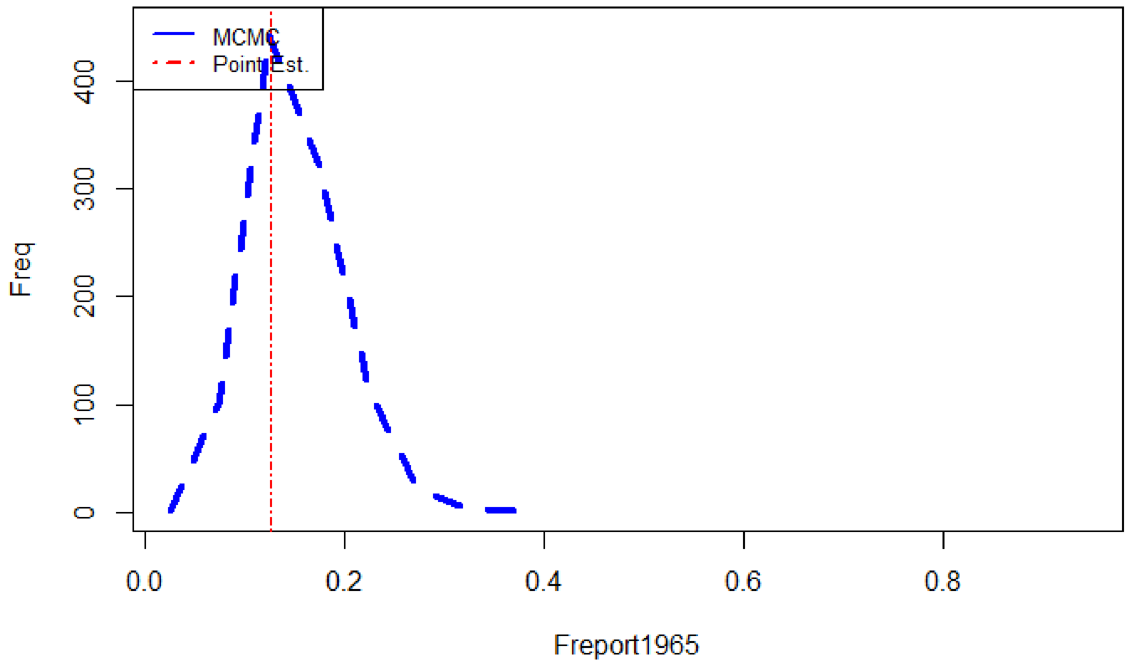

5th, 95th
Median
Point Est.
Freport
Year
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017

Figure B4- 27 Posterior density of Atlantic herring SSB and F in 1965 and 2017 from the MCMC of the base ASAP model




MCMC
Point Est.
Freq
0
100
200
300
400
0.0
0.2
0.4
0.6
0.8
Freport1965

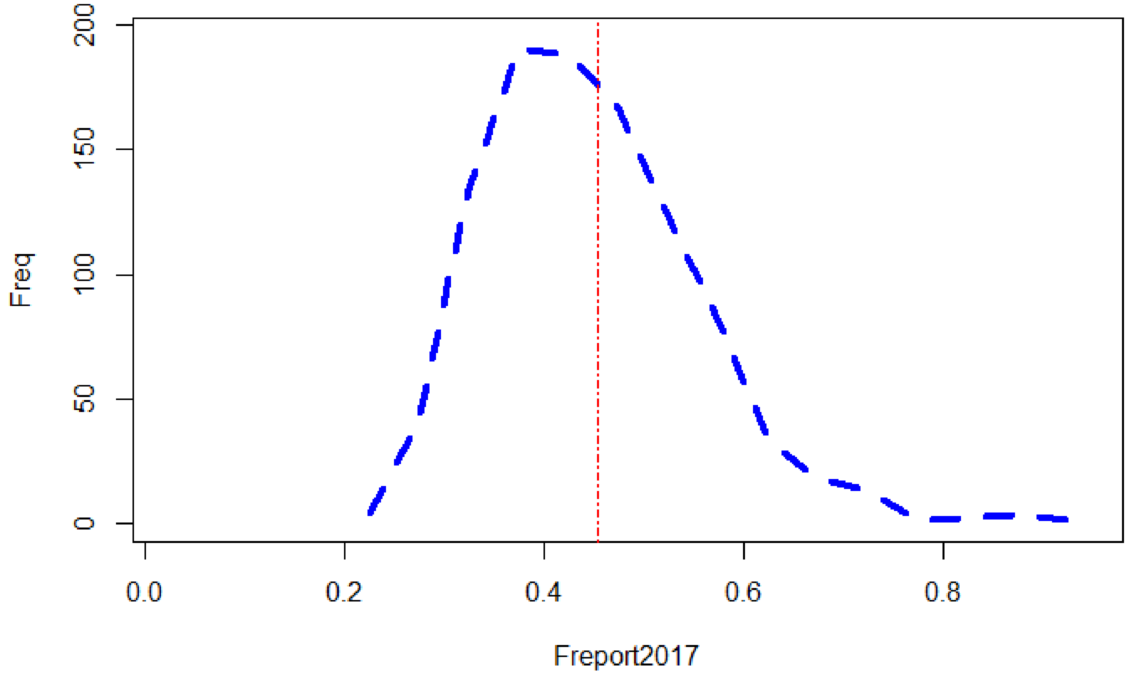

Freq
0
50
100
150
200
0.0
0.2
0.4
0.6
0.8
Freport2017

Figure B4- 28 Internal retrospective pattern for F, SSB, and recruitment for the base ASAP model

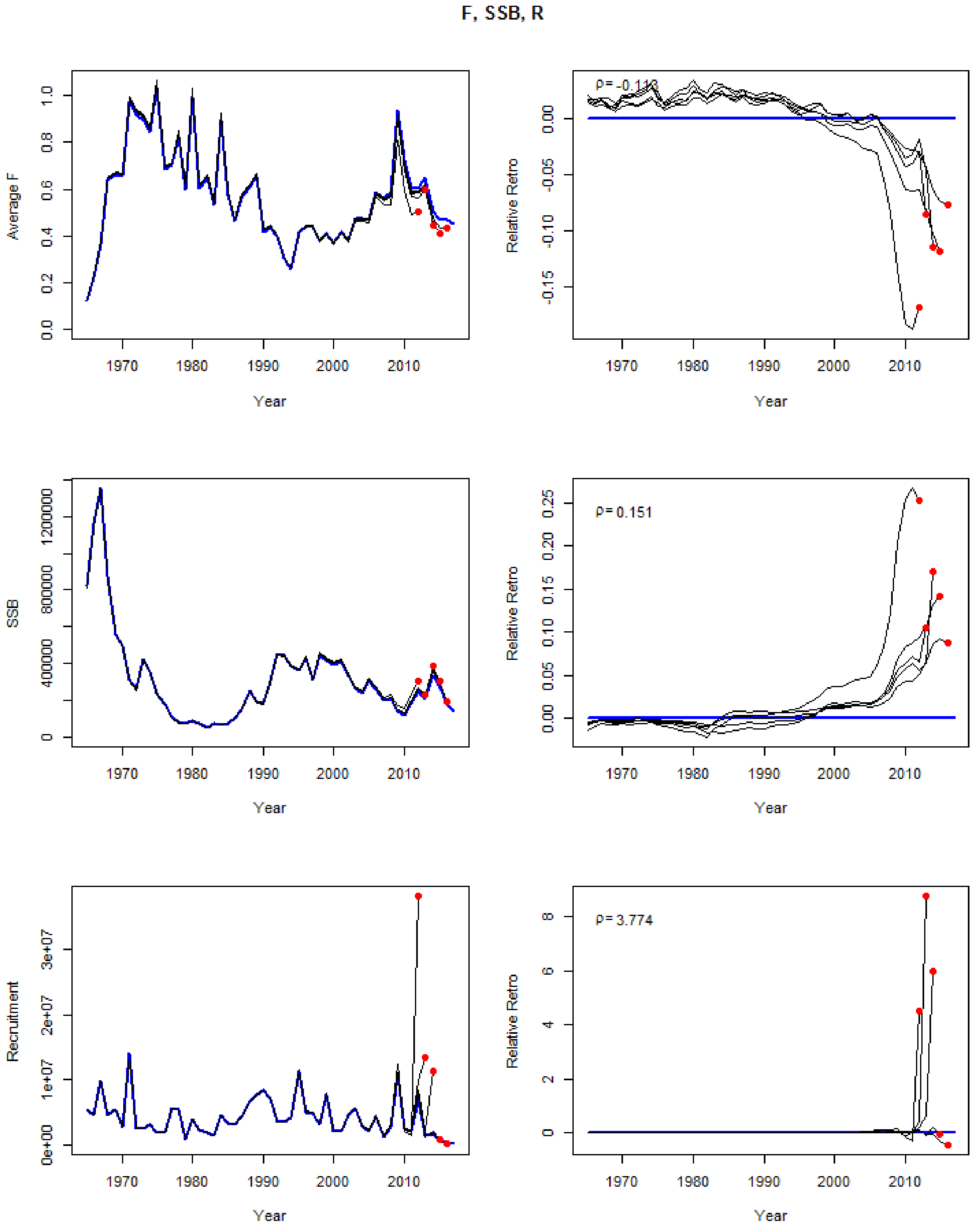
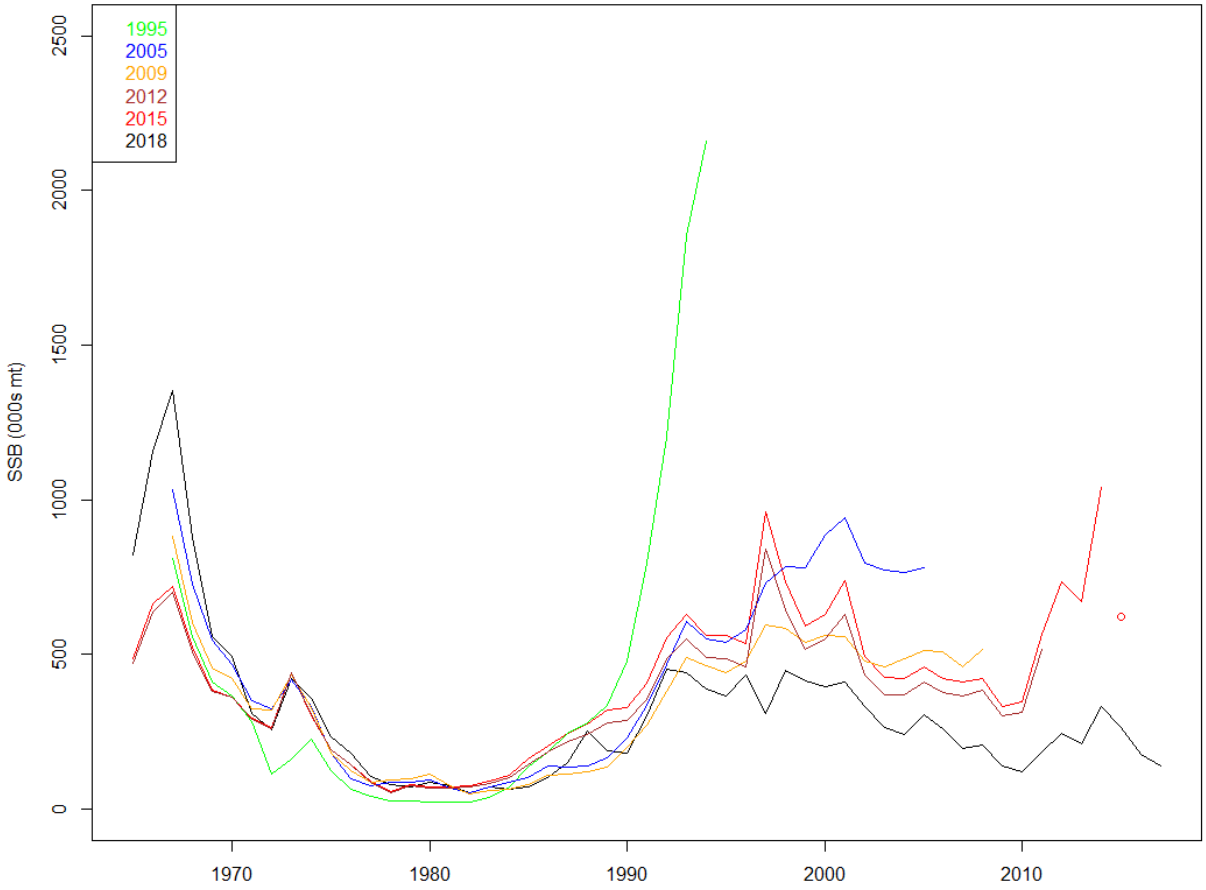
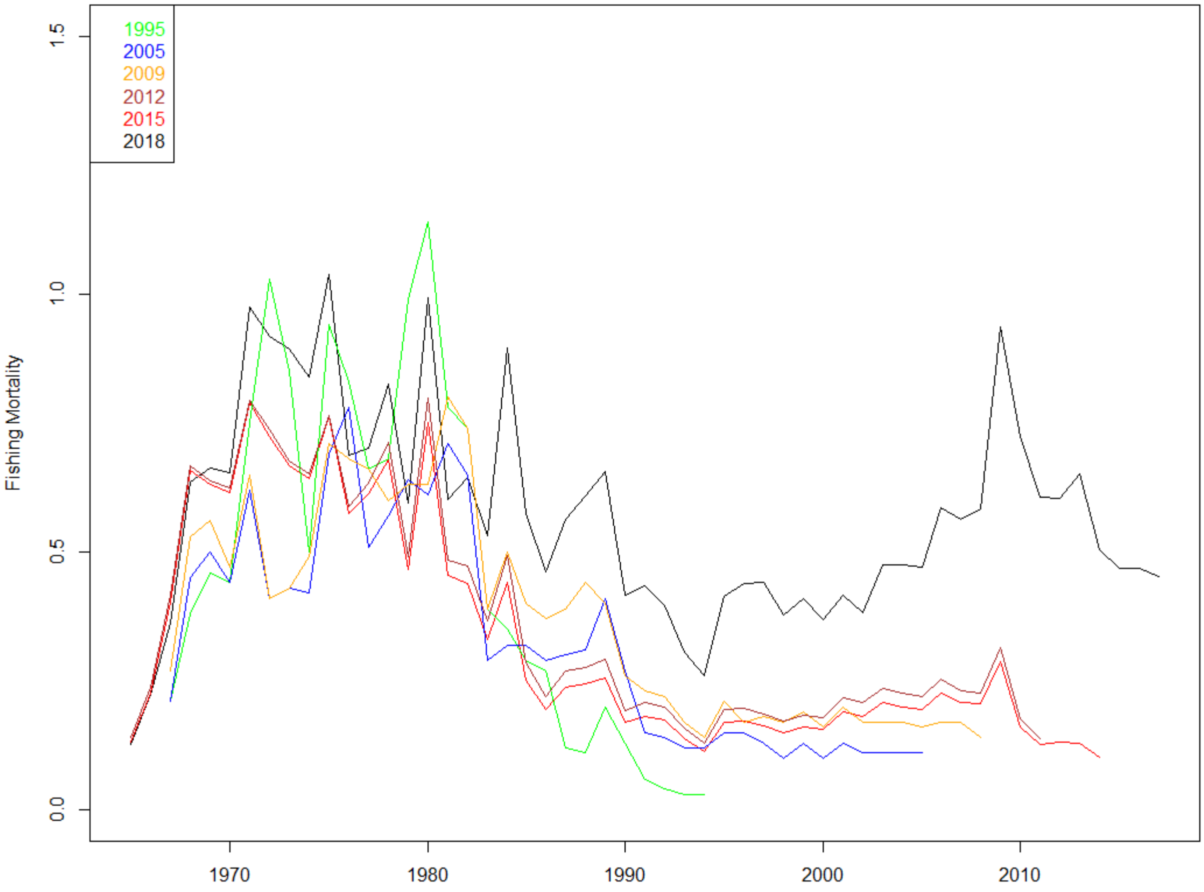


Figure B4- 29 Atlantic herring historic retrospective pattern for SSB, F (not directly comparable), and F rescaled by each time series mean to make the trends more readily comparable




1995
2005
2009
2012
2015
2018
Fishing Mortality
0.0
0.5
1.0
1.5
1970
1980
1990
2000
2010

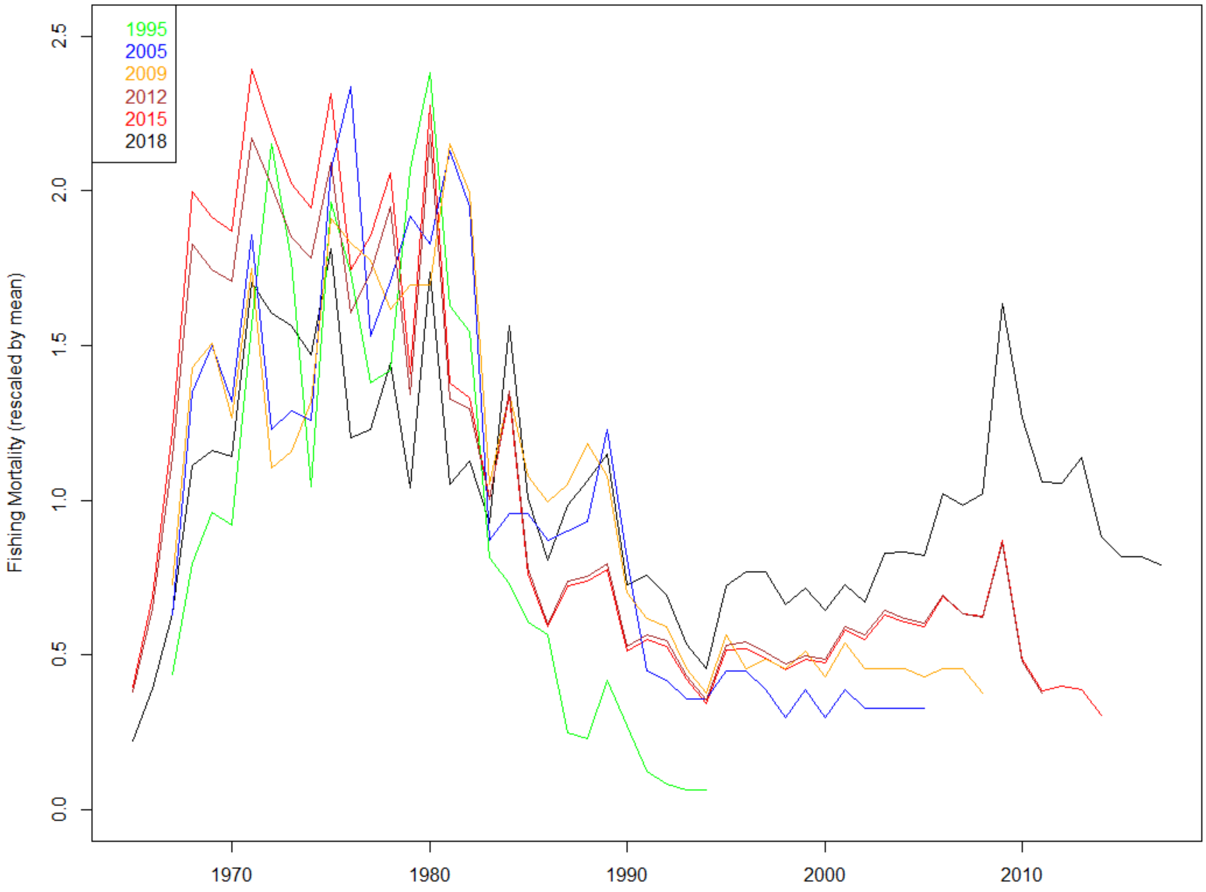
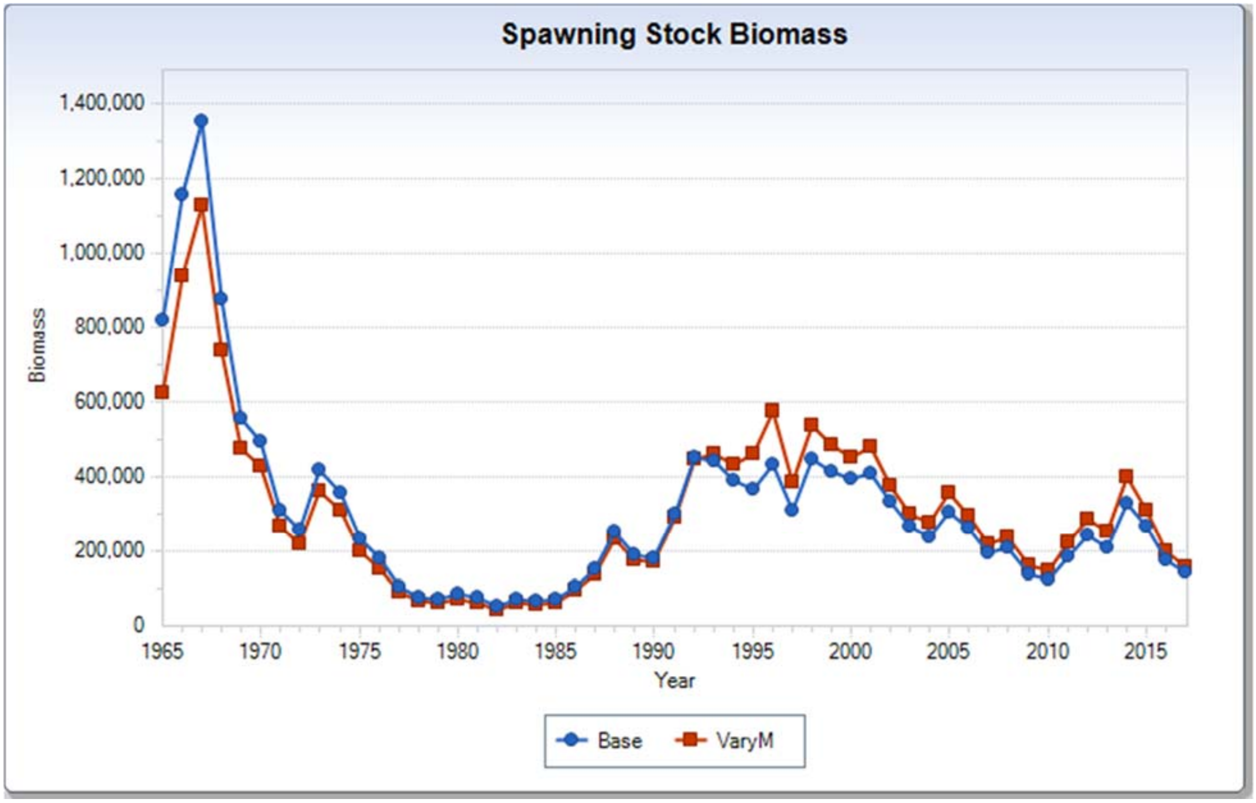

1995
2005
2009
2012
2015
2018
Fishing Mortality (rescaled by mean)
0.0
0.5
1.0
1.5
2.0
2.5
1970
1980
1990
2000
2010

Figure B4- 30 Atlantic herring SSB and recruitment time series for the base ASAP model (Base) and the base model amended to have age- and time-varying M (VaryM)



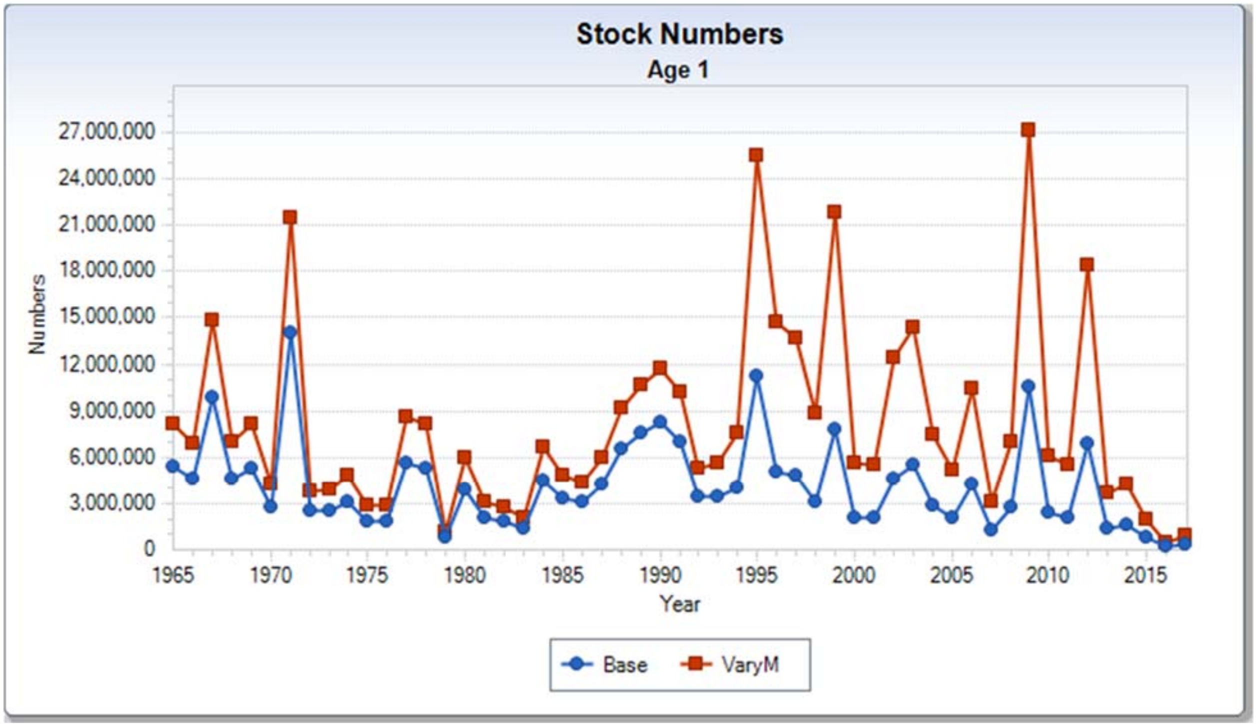


Figure B4- 31 Retrospective patterns for the base model except with age- and time-varying M

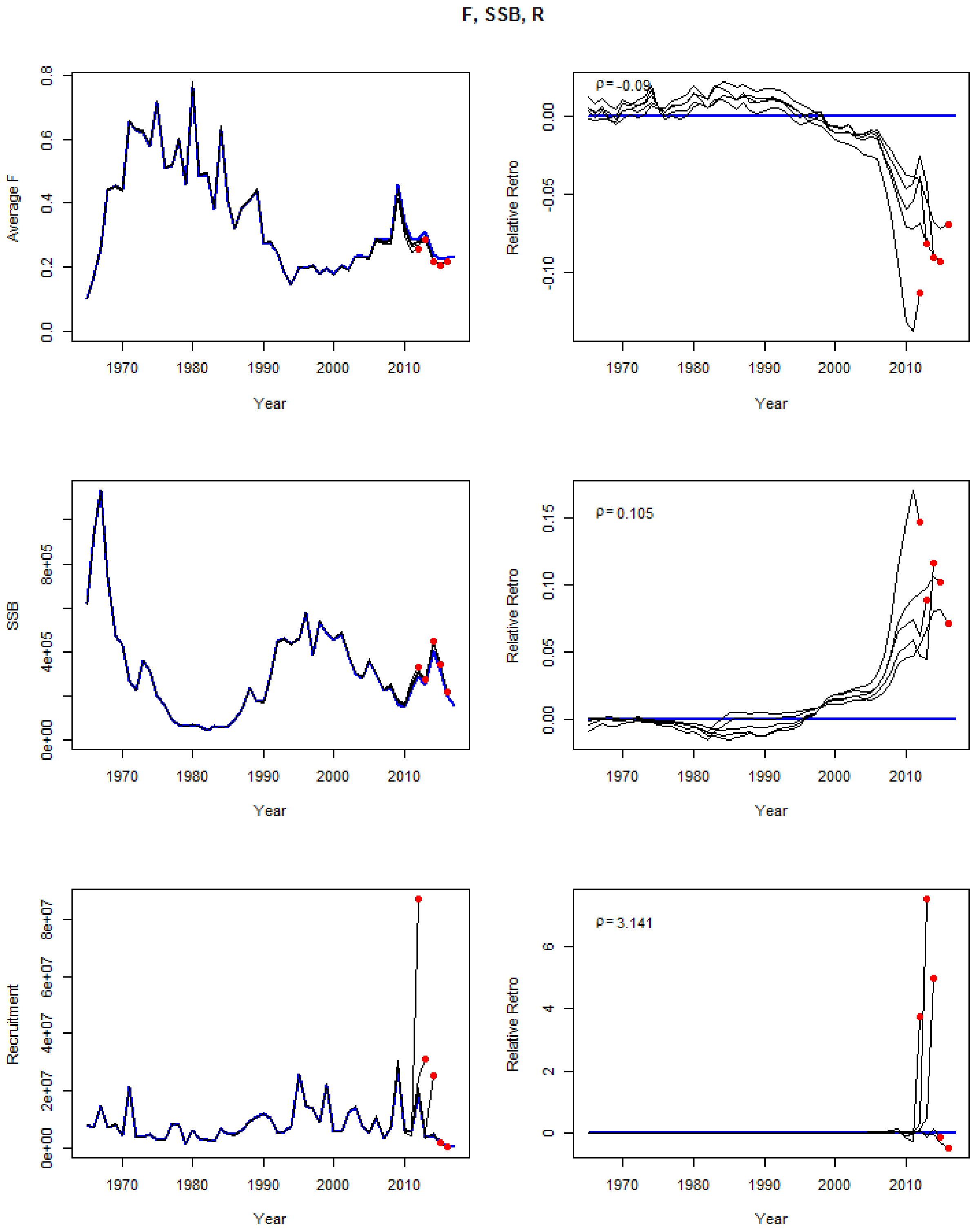


Figure B4- 32 Atlantic herring SSB and recruitment time series for the base ASAP model (Base) and the base model amended to have age-varying M (LorM)

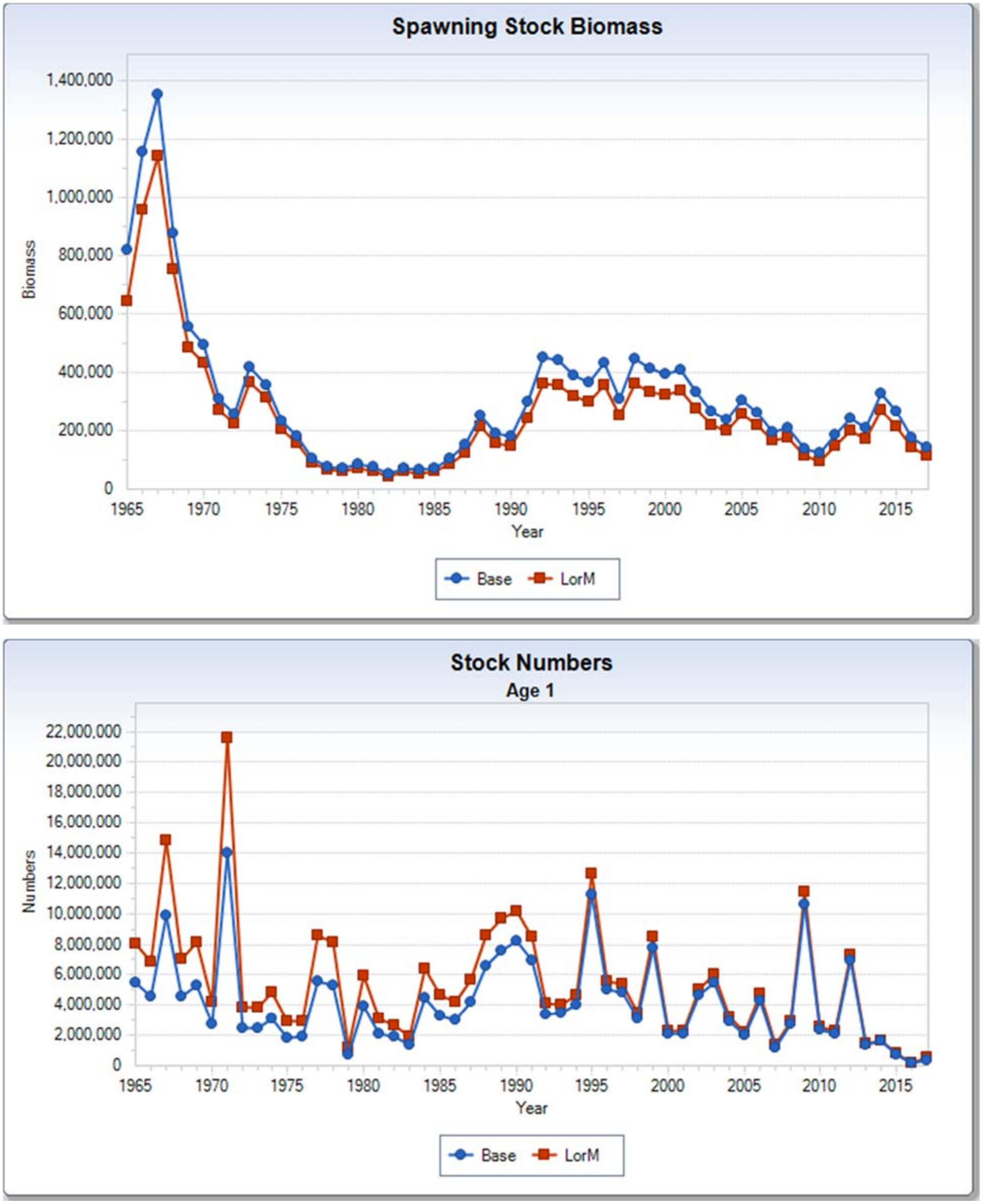


Figure B4- 33 Retrospective pattern for the base model amended to have age-varying M

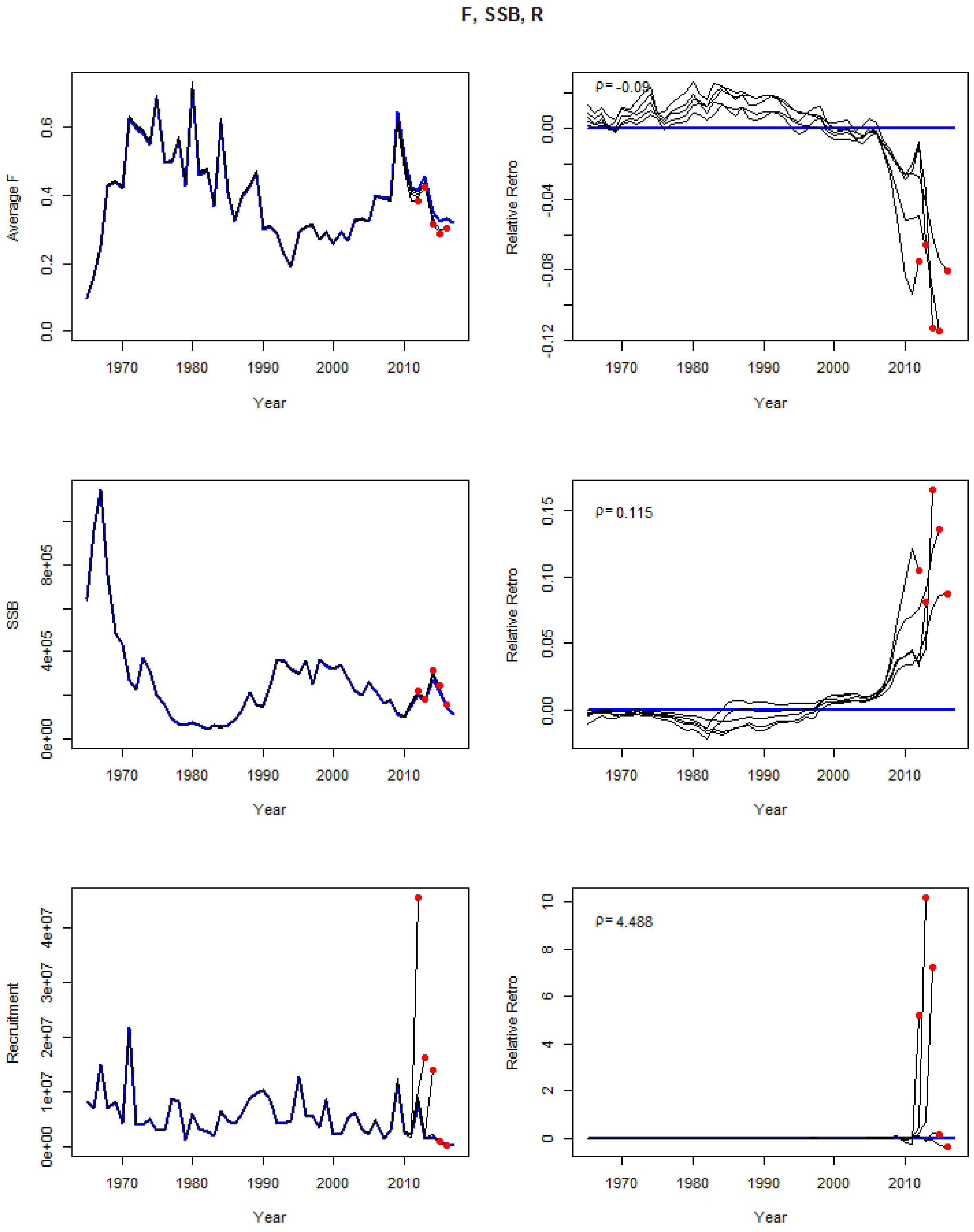
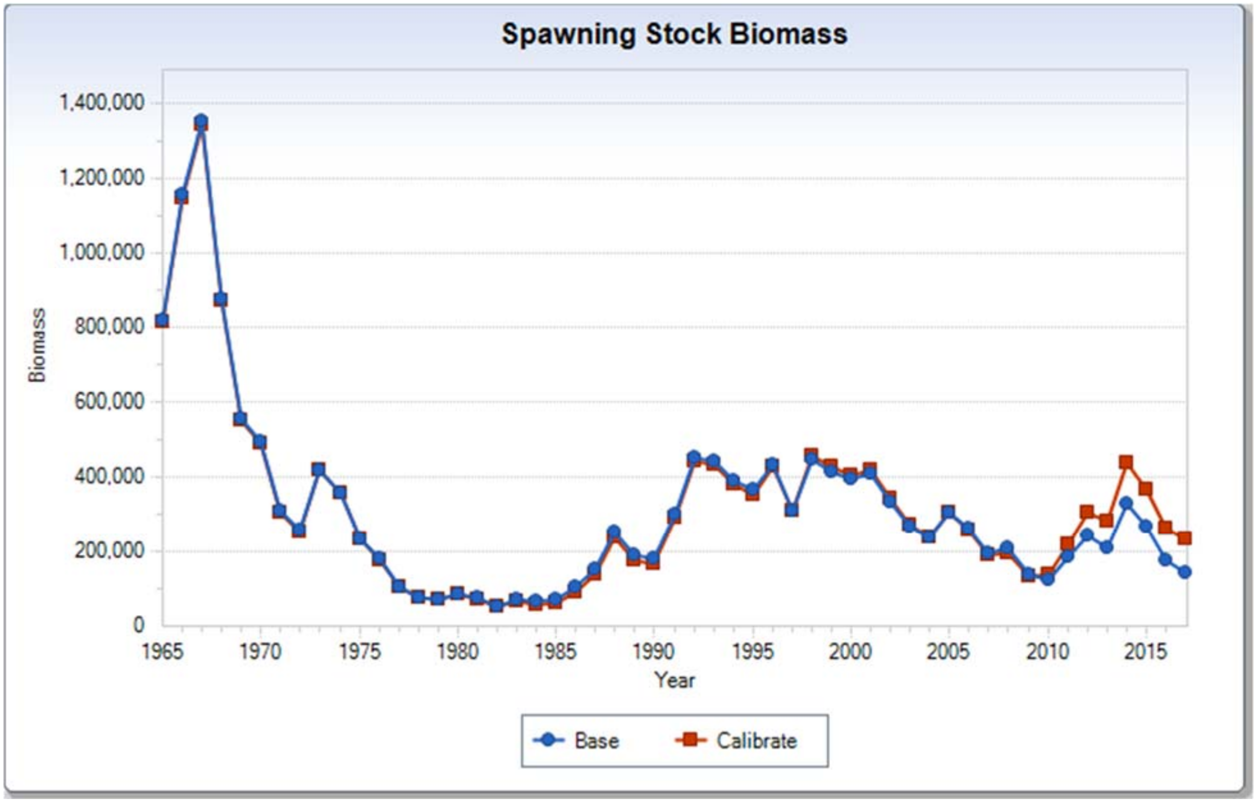


Figure B4- 34 Atlantic herring SSB and recruitment time series for the base ASAP model (Base) and the base model amended to with the NMFS spring and fall Bigelow years (2009-2017) calibrated to Albatross equivalents (Calibrate)



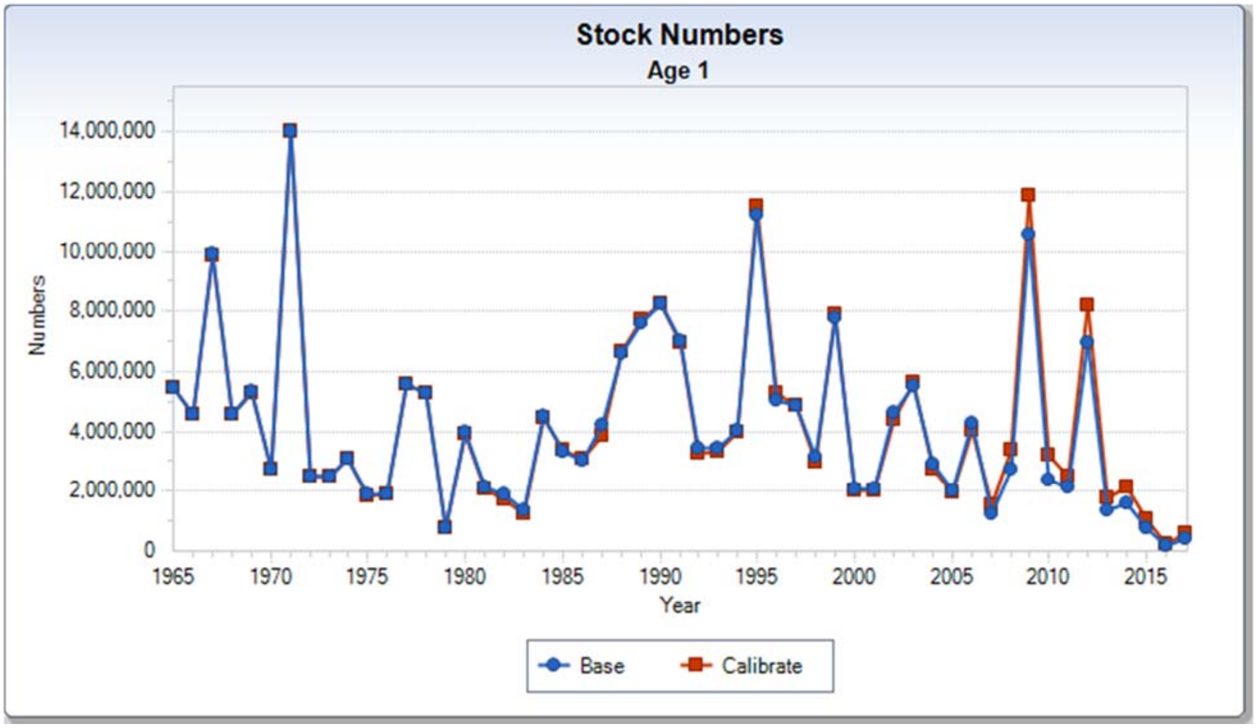


Figure B4- 35 Retrospective pattern for the base model amended to with Bigelow catches (2009-2017) calibrated to Albatross equivalents

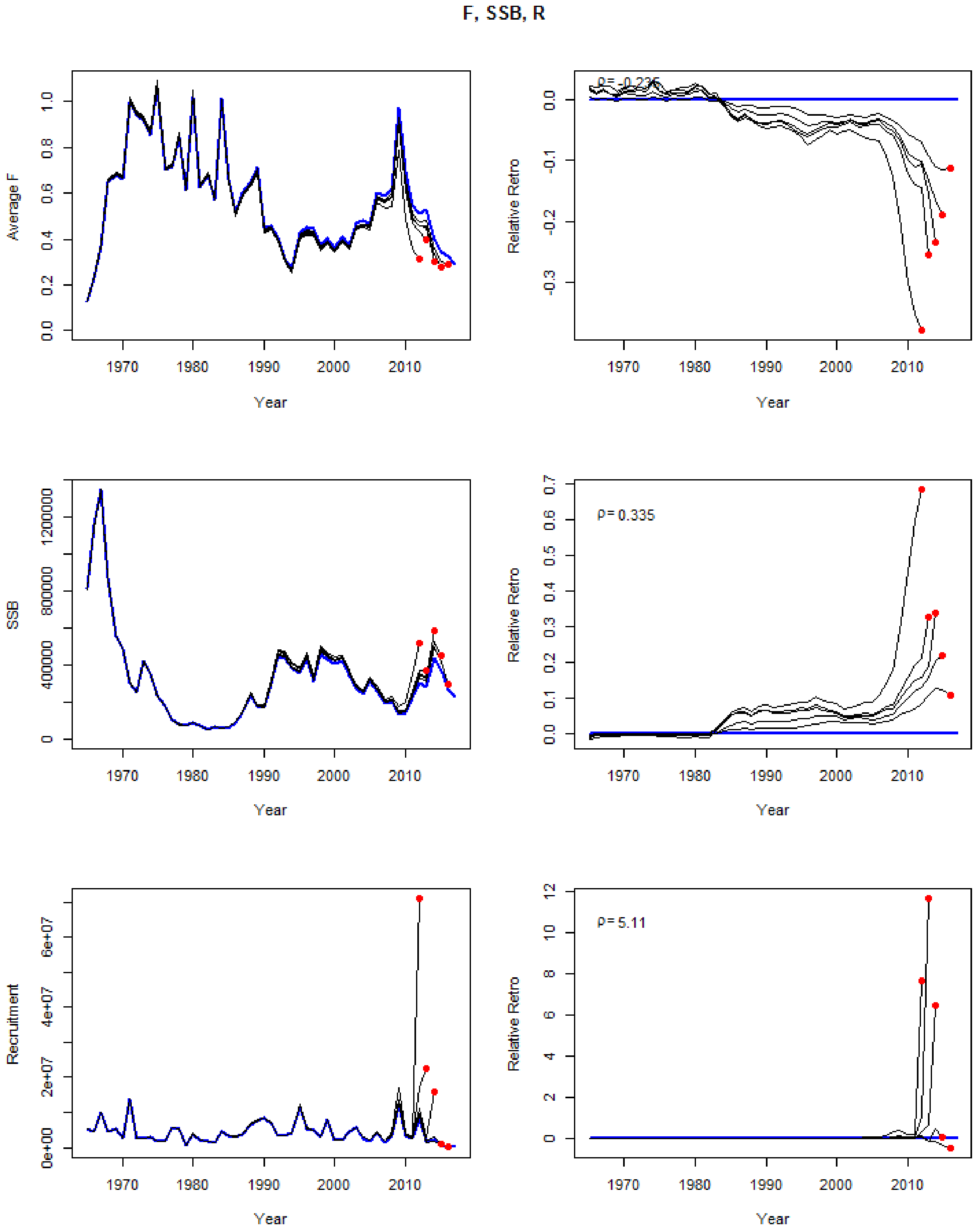


Figure B4- 36 Ratio of Bigelow to Albatross catchability as estimated by ASAP and using paired tow experiments (Conversion Coeff.). Bottom panel is the black bar value divided by the blue bar value in the top panel

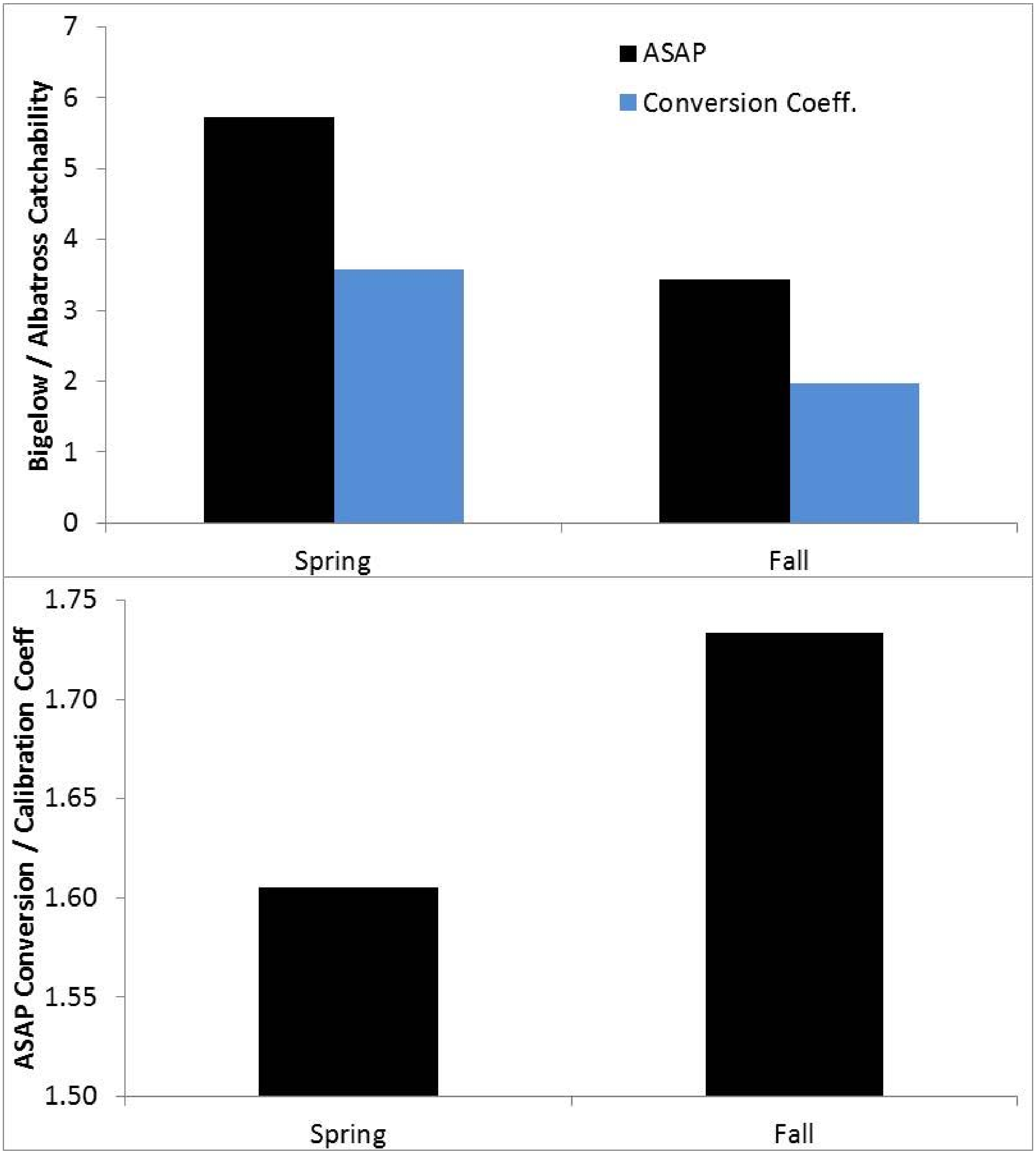
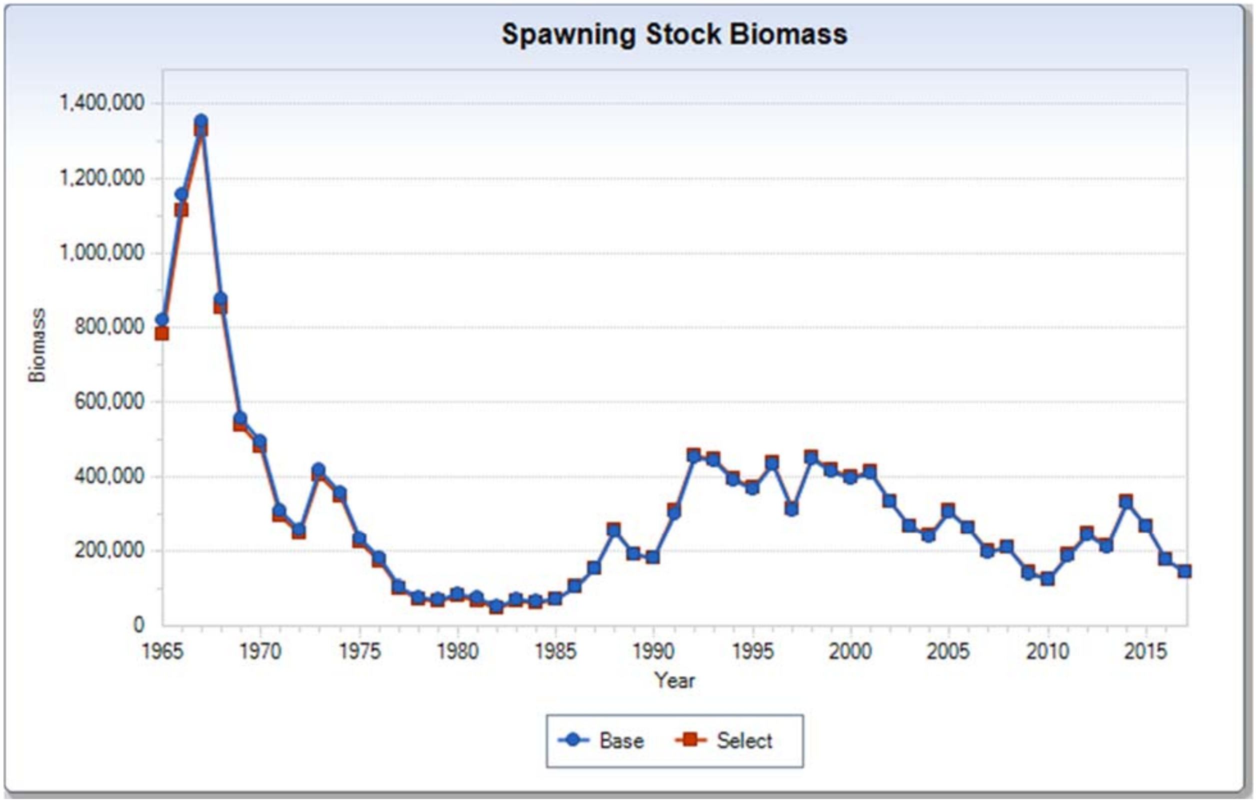


Figure B4- 37 Atlantic herring SSB and recruitment time series for the base ASAP model (Base) and the base model amended with a selectivity block in the mobile fleet (Select)



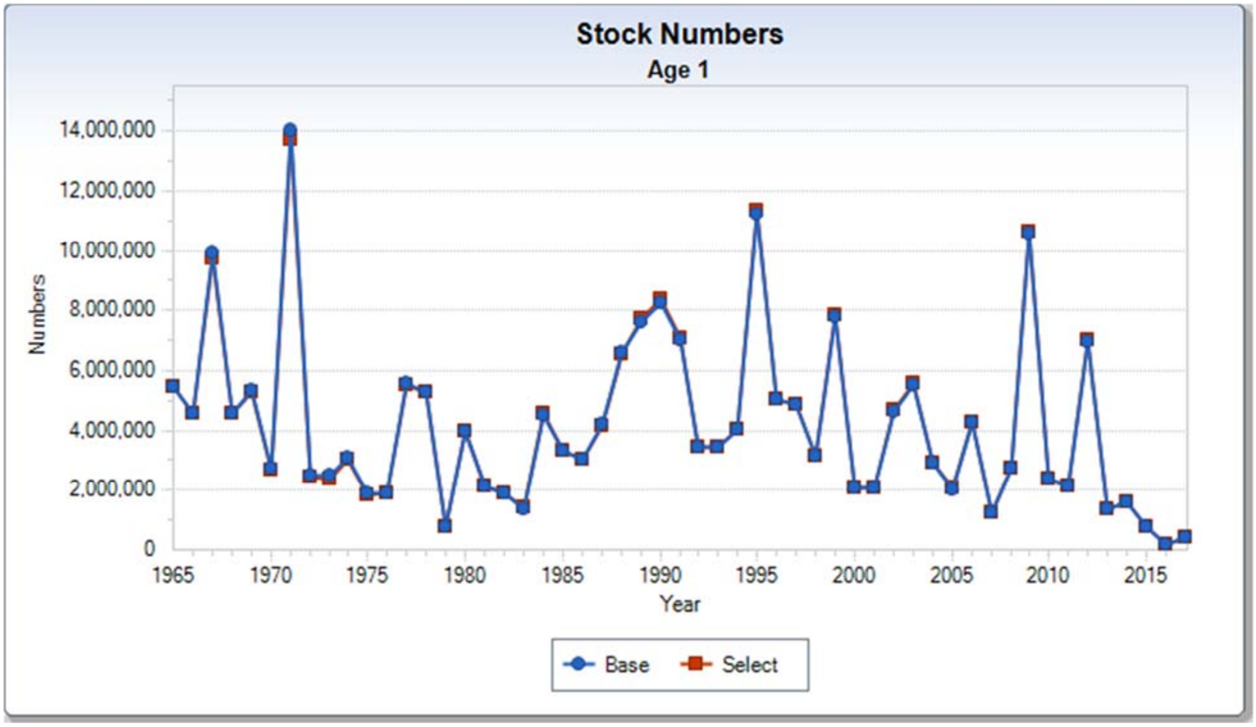


Figure B4- 38 Retrospective pattern for the base model amended with a selectivity block in the mobile fleet

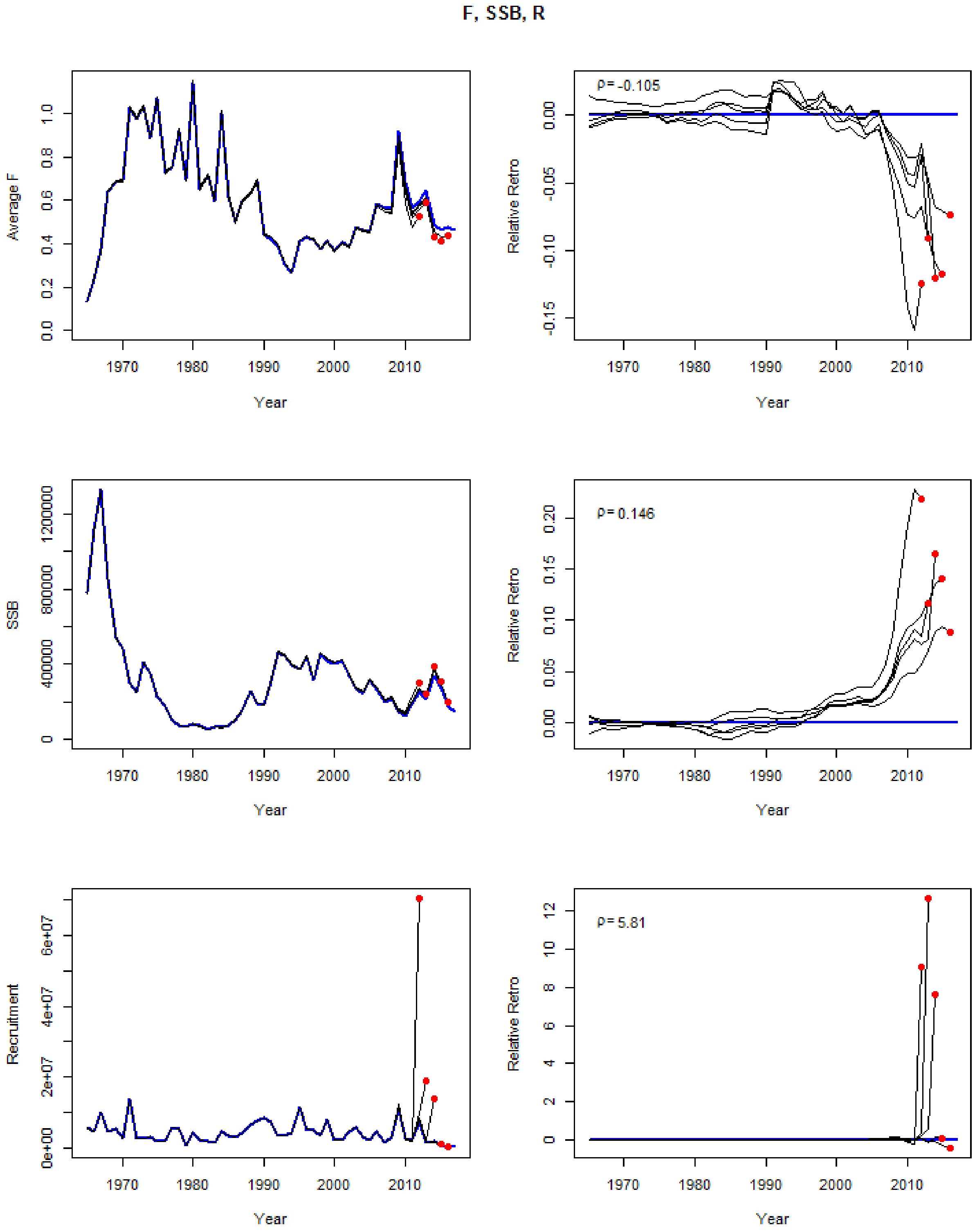
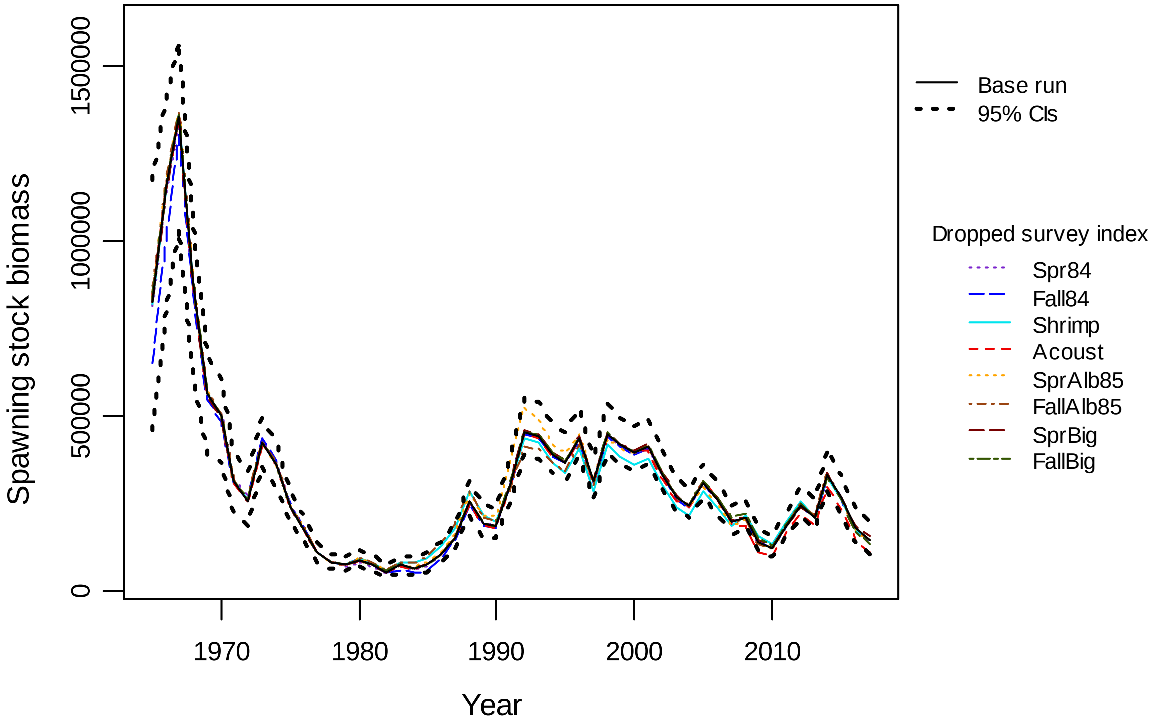


Figure B4- 39 Atlantic herring SSB time series produced by excluding one survey at a time from the base model (top panel) and highlighting the difference between the base and excluding the acoustic index (bottom panel)



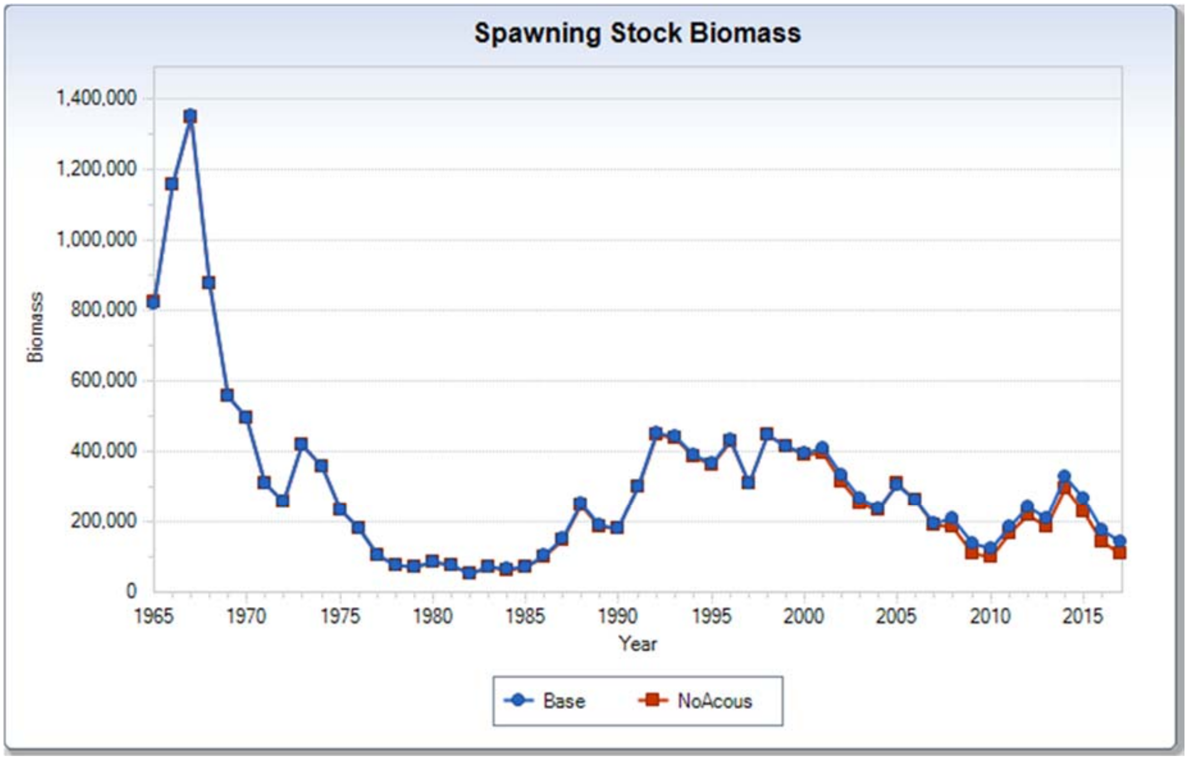


Figure B4- 40 Retrospective pattern for the base model except with the acoustic index excluded from the fit

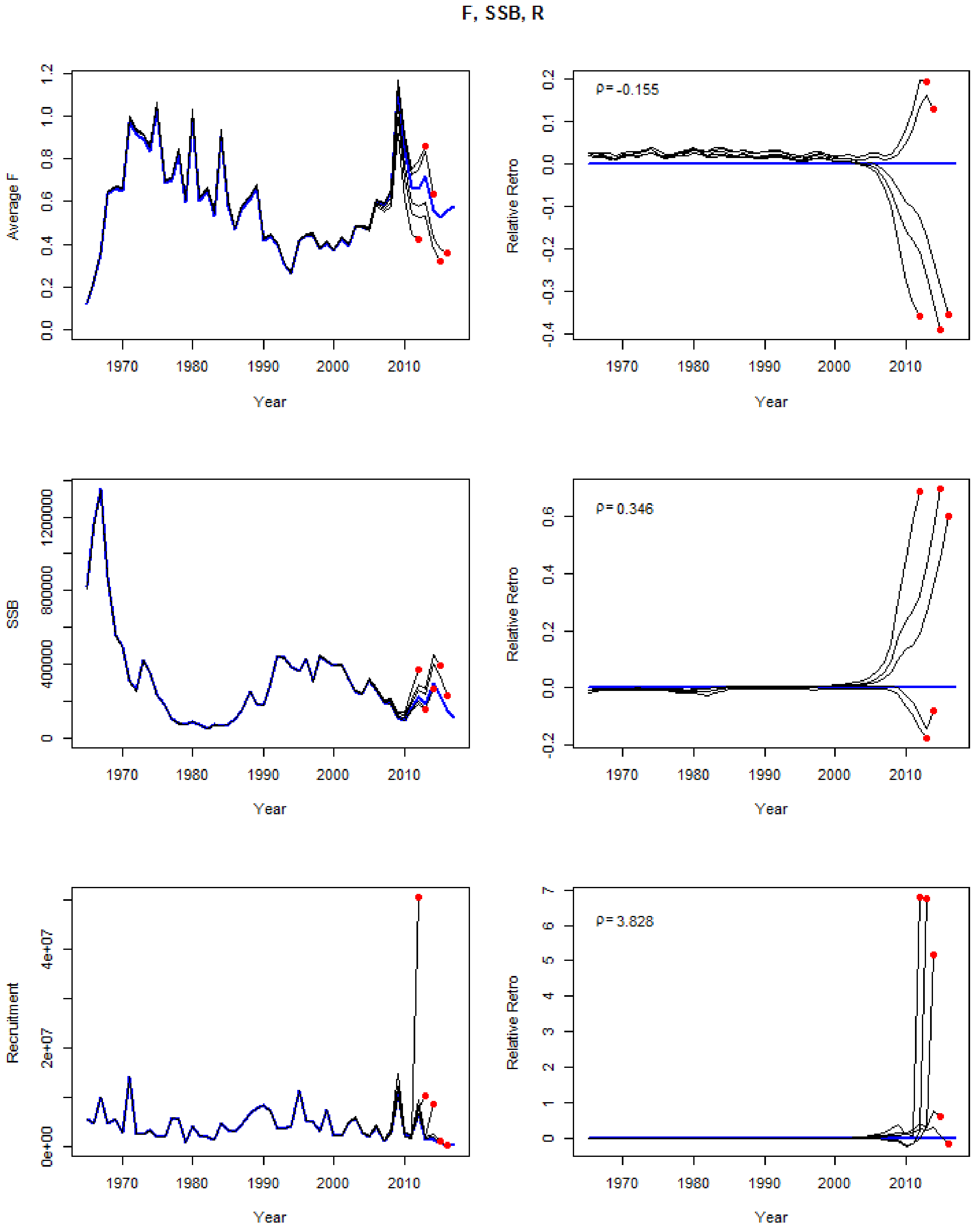


Figure B4- 41 Stock status for the Atlantic herring base model except with the exclusion of the acoustic index from the fit

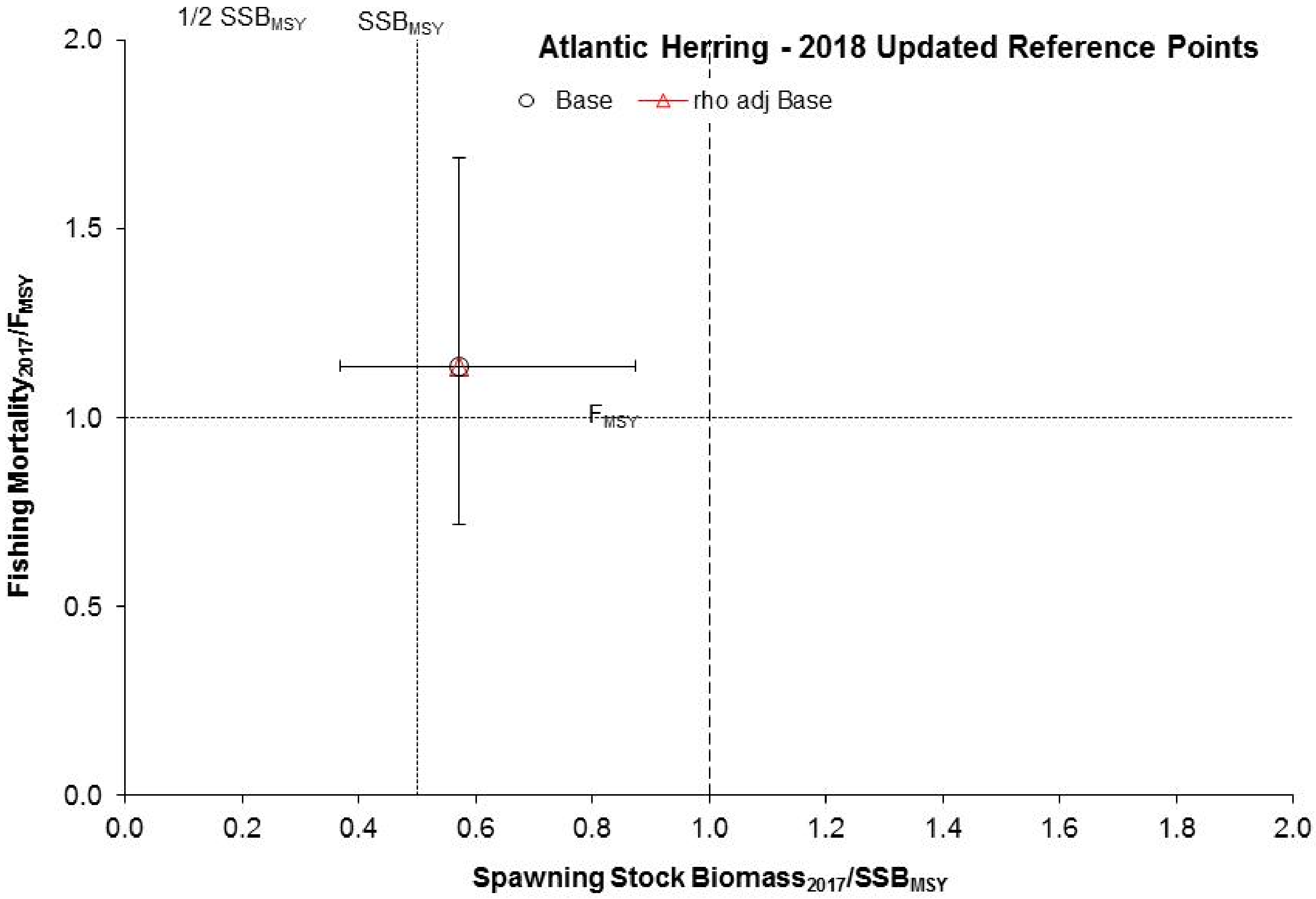


Figure B4- 42 Atlantic herring SSB time series for the base model and the base model with the addition of the index of abundance derived from food habits data

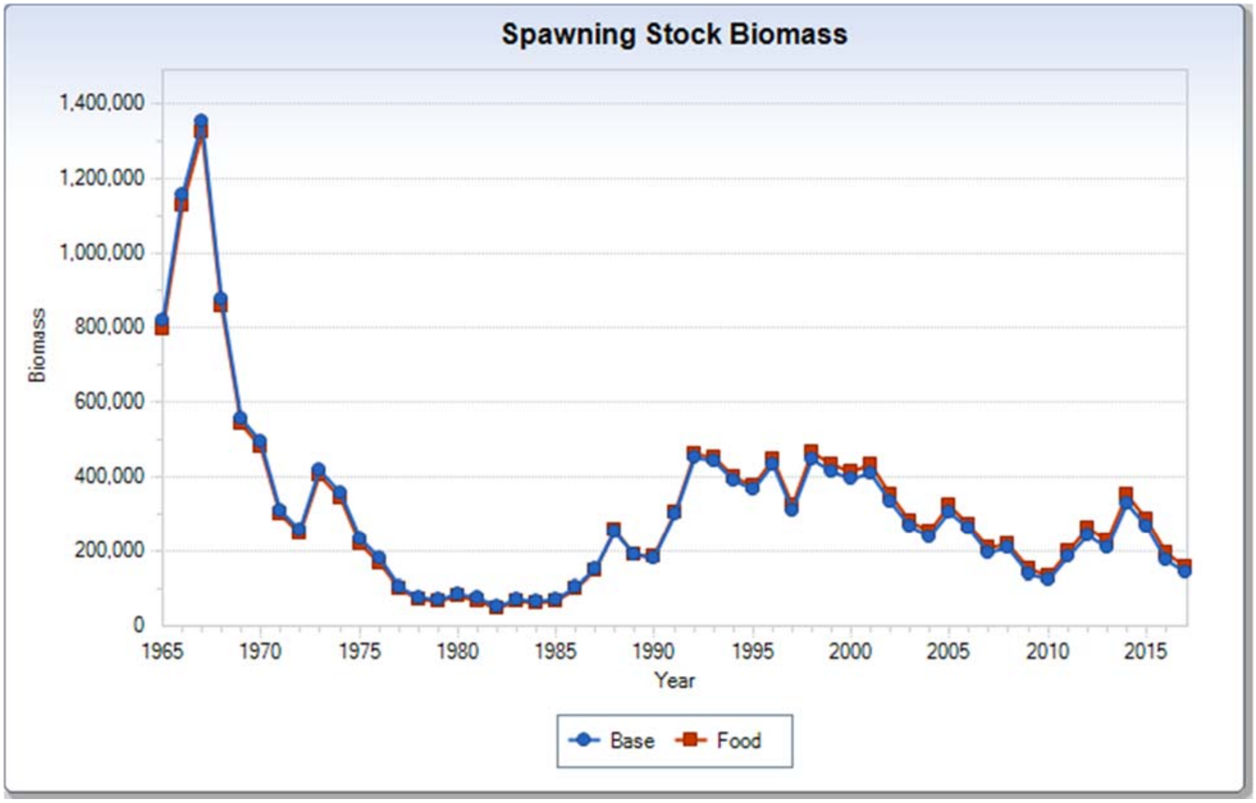
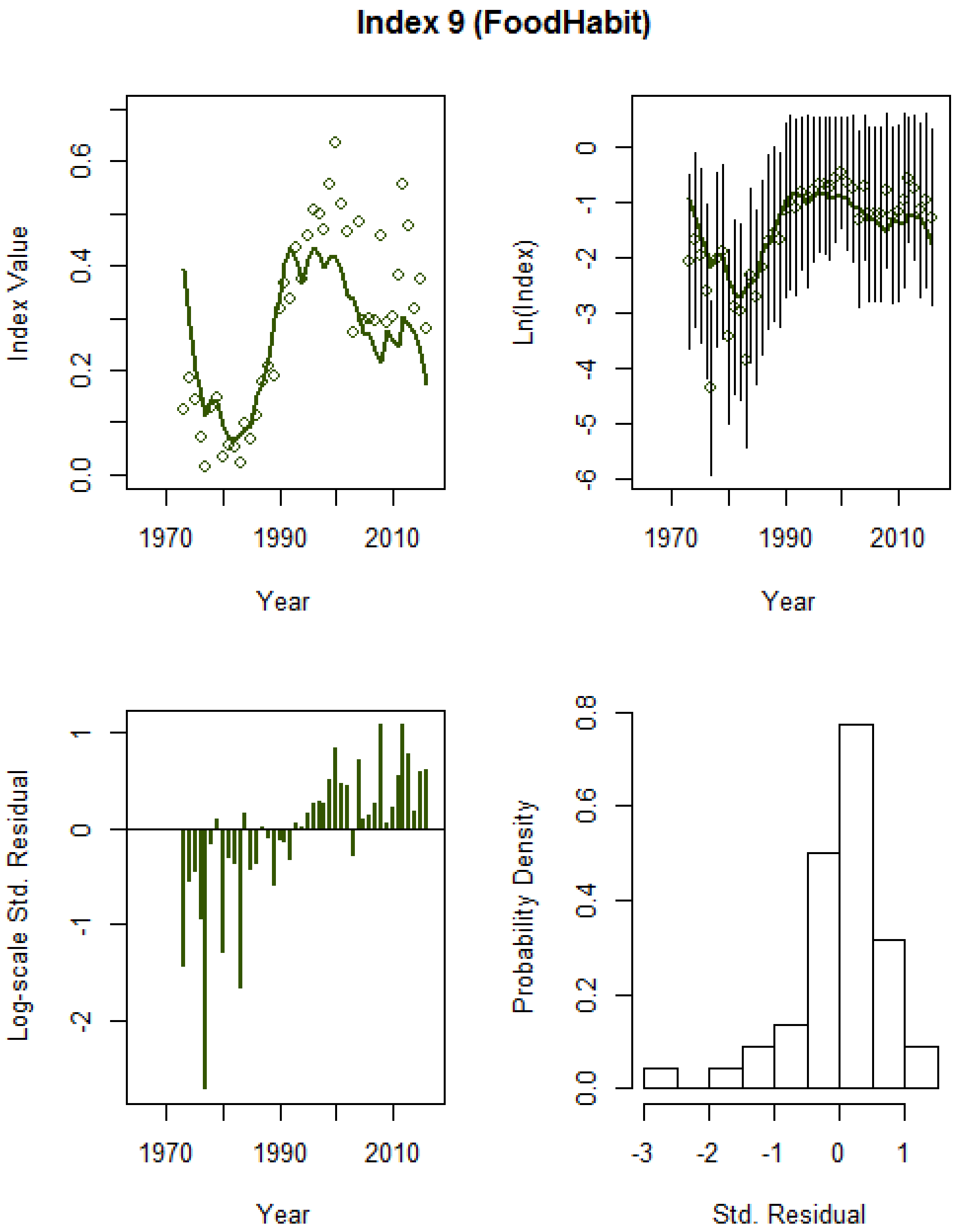


Figure B4- 43 Fit to the food habits index when added to base ASAP model



TOR B5: *State the existing stock status definitions for "overfished" and "overfishing". Then update or redefine biological reference points (BRPs; point estimates or proxies for B_{MSY}, $B_{THRESHOLD}$, F_{MSY} and MSY) and provide estimates of their uncertainty. If analytic model-based estimates are unavailable, consider recommending alternative measurable proxies for BRPSs. Comment on the scientific adequacy of existing BRPs and the "new" (i.e. updated, redefined , or alternative) BRPs.*

The existing MSY reference points were based on the fit of a Beverton-Holt stock-recruitment relationship, estimated internally to the ASAP model, and inputs (e.g., weights-at-age, natural mortality) from the terminal year of the assessment (i.e., 2014). Point estimates of the MSY BRPs equaled: MSY = 77,247 mt, F_{MSY} = 0.24, and SSB_{MSY} = 311,145 mt.

No stock-recruit relationship was able to be estimated in the base ASAP model, therefore $F_{40\%}$ was used as a proxy for F_{MSY} and long-term projections were used to derive other MSY BRP proxies. The average of the last five years (2013-2017) of weights at age and maturity at age were used to calculate $F_{40\%}$ and in long-term projections. Selectivity at age equaled the catch weighted average of the selectivities at age from the mobile and fixed fleets over the last five years, which produced selectivity generally similar to the mobile fleet given that this fleet accounts for most of the catch in those years. Recruitment in each year of the projections was drawn from the empirical cumulative distribution of the estimated recruitments from 1965-2015. The estimates of recruitment from 2016-2017 were excluded because they were imprecisely estimated with CVs equal to 95% and 251%, respectively (as a point of comparison the CV for 2015=38%; Figure B4- 19). In drawing recruitments from the empirical distribution, a uniform random value is drawn between 0-1 each year, and the recruitment associated with that probability from the cumulative distribution is applied. Thus, any recruitment between the minimum and maximum in the estimated time series has an equal probability of selection each year. F_{MSY} proxy = 0.51, SSB_{MSY} proxy = 189,000 mt (½ SSB_{MSY} = 94,500 mt), and MSY proxy = 112,000 mt.

Metric	Point Estimate	80% probability interval
F_{MSY}	0.51	NA
SSB_{MSY}	189,000 mt	128,000 – 278,000 mt
MSY	112,000 mt	78,000 – 157,000 mt

The existing MSY reference points were based on estimates of a Beverton-Holt stock-recruit curve fit internally to the ASAP model (NEFSC 2012; Deroba 2015). The ability to estimate the stock-recruit curve seems to have deteriorated in this assessment and was not supported. The deterioration in the models ability to estimate a stock-recruit curve is likely related to changes in model structure, such as in M and various likelihood penalties (see TOR B4). Although, the 2012 assessment (NEFSC 2012) reported similar estimation issues as in this assessment (e.g., flat likelihood profile over steepness; steepness and unfished SSB highly correlated), and so the ability of previous models to estimate a stock-recruit curve was also tenuous. The newly proposed reference points no longer rely on a poorly estimated stock-recruit relationship.

TOR B6: *Make a recommendation about what stock status appears to be based on the existing model (from previous peer reviewed accepted assessment) and based on a new model or model formulation developed for this peer review.*

a. Update the existing model with new data and evaluate stock status (over fished and overfishing) with respect to the existing BRP estimates.

Given the Working Group's conclusion that MSY reference points based on the estimation of a stock-recruit curve were unjustified, and were likely unjustified in previous assessments, the existing BRPs are not meaningful. Similarly, evaluating stock status of the existing model with updated data to the existing MSY BRPs is not informative.

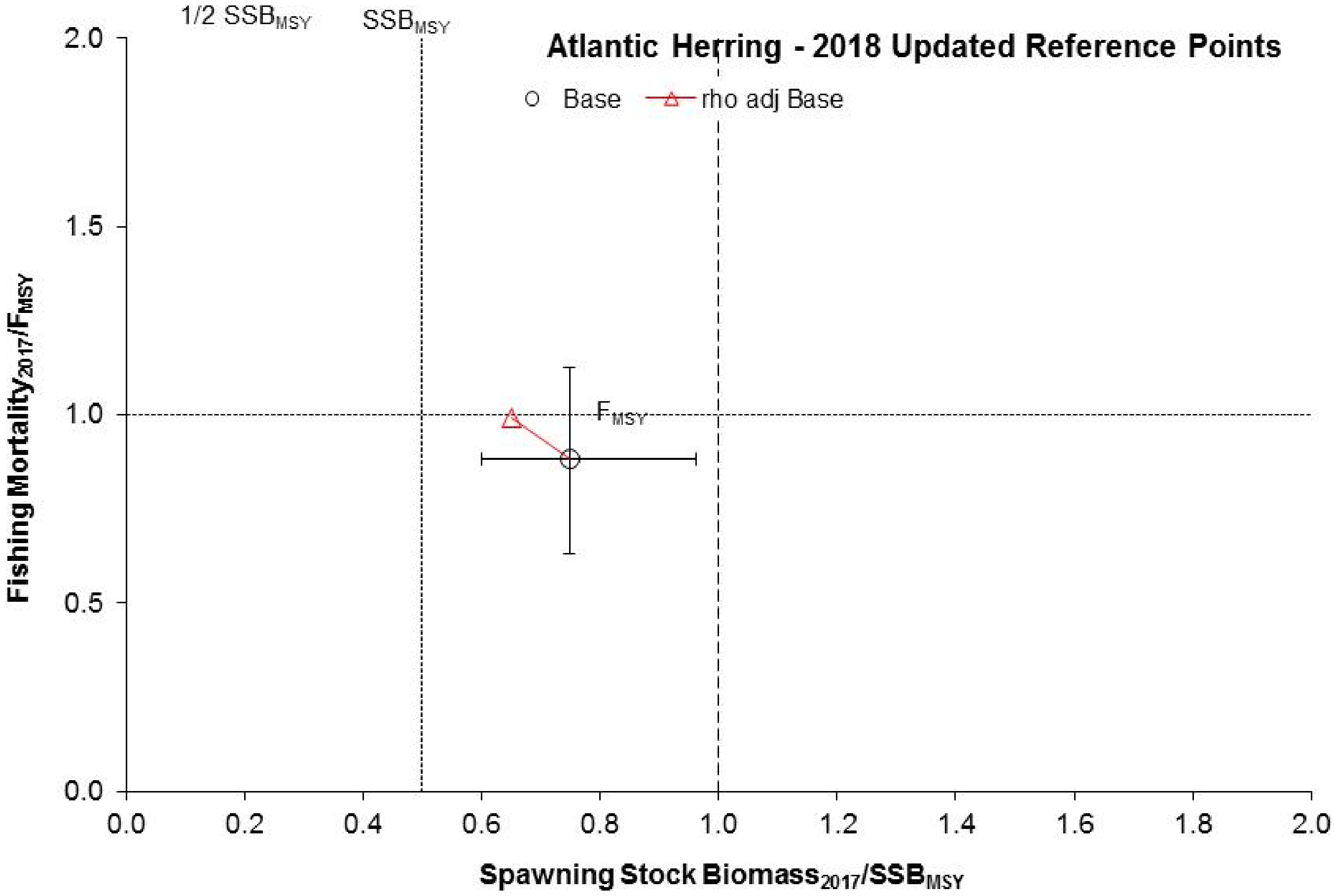
b. Then use the newly proposed model and evaluate stock status with respect to "new" BRPs and their estimates (from TOR B5).

The base ASAP model estimated $F_{7\text{-}8}$ (see TOR B5) in 2017 to be 0.45 and SSB in 2017 was 141,000 mt. Since the retrospective adjusted values do not fall outside of the confidence intervals of the base model estimates, no retrospective adjustment was warranted. A comparison of the base model values to the new MSY proxy reference points suggest that overfishing is not occurring and that the stock is not overfished (Figure B6- 1). The error bars for $F_{7\text{-}8}$, however, included overfishing (Figure B6- 1).

c. Include descriptions of stock status based on simple indicators/metrics.

The estimated numbers at age in 2017 indicate that the population is characterized by more age 6 fish than age 1 and age 2 combined. This result suggests a reliance on the ageing 2011 cohort (age 6 in 2017). If the estimated record low recruitments in recent years hold true, then the SSB is likely to remain relatively low and put the stock at relatively high risk of becoming overfished. Without improved recruitment, the probability of overfishing under recent catch levels is also likely relatively high.

Figure B6- 1 Stock status, “Kobe plot”, for the base ASAP model ± 80% CI.



TOR B7: Develop approaches and apply them to conduct stock projections.

a. Provide numerical annual projections (through 2021) and the statistical distribution (i.e. probability density function) of the catch at F_{MSY} or an F_{MSY} proxy (i.e. overfishing level, OFL) (see Appendix to the SAW TORs). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass. Use a sensitivity analysis approach in which a range of assumptions about the most important uncertainties in the assessment are considered (e.g. terminal year abundance, variability in recruitment).

Short-term projections of future stock status were conducted based on the results of the base ASAP model. The projections did not account for any retrospective pattern because the Mohn's Rho adjusted values for stock status were within the 80% probability intervals of the 2017 point estimates of F_{7-8} and SSB (Figure B6- 1; TOR B6). Numbers at age for ages 2-8+ in 2018 (the first year of the projection) were drawn from 1000 vectors of numbers at age produced from MCMC simulations of the base ASAP model (see TOR B4 for description of MCMC). Age 1 recruitment in 2018 was drawn from 1000 values, with each value representing the geometric mean of the estimated recruitments for 2013-2017 from each of the 1000 MCMC simulations of the base ASAP model. Age 1 recruitment in 2019-2021 was drawn from the empirical cumulative distribution of the estimated recruitments from 1965-2015 from the base ASAP model (2016 and 2017 were excluded due to imprecision; TOR B5). All other inputs were the same as described in TOR B5.

Projections were repeated with catch in 2018 equal to: 1) the 2018 allowable biological catch (111,000 mt), or 2) half the 2018 allowable biological catch (55,000 mt). Regardless of the catch value in 2018, fishing mortality in 2019-2021 equaled the Fmsy proxy (0.51; TOR B5), and so the row of "Catch (mt)" in the tables below represents the catch at the Fmsy proxy.

	2018	2019	2020	2021
Catch (mt)	111,000	13,700	31,000	55,700
Catch 80% CI	NA	4,000-36,600	16,000-62,700	32,100-95,500
F$_{7-8}$	1.7	0.51	0.51	0.51
F$_{7-8}$ 80% CI	0.83-4	NA	NA	NA
SSB (mt)	32,900	19,700	31,700	85,800
SSB 80% CI	4,700-78,600	5,200-58,700	16,500-71,300	47,500-159,000
P(overfishing)	0.95	NA	NA	NA
P(overfished)	0.96	0.94	0.93	0.58

	2018	2019	2020	2021
Catch (mt)	55,000	28,900	38,000	59,400
Catch 80% CI	NA	17,200-53,100	22,700-70,800	35,300-99,600
F$_{7-8}$	0.58	0.51	0.51	0.51
F$_{7-8}$ 80% CI	0.4-0.86	NA	NA	NA
SSB (mt)	75,300	43,500	42,600	91,000
SSB 80% CI	46,900-112,100	25,800-86,100	26,400-87,900	52,400-166,100
P(overfishing)	0.69	NA	NA	NA
P(overfished)	0.76	0.92	0.91	0.53

b. Comment on which projections seem most realistic. Consider the major uncertainties in the assessment as well as sensitivity of the projections to various assumptions. Identify reasonable projection parameters (recruitment, weight -at-age, retrospective adjustments, etc.) to use when setting specifications.

The Working Group agreed that the 2018 ABC of 111,000mt is unlikely to be fully utilized and that a value of 55,000mt is more realistic. The exact value for 2018 catch that should ultimately be used is best left to the Atlantic herring Plan Development Team of the New England Fishery Management Council. Other uncertainties were addressed in TOR B4. The projections assume the future recruitment will approach the mean for the time series. If recruitment continues to be below average, the projected catch increases may be overly optimistic.

c. Describe the stock's vulnerability (see "Appendix to the SARC TORs") to becoming overfished, and how this could affect the choice of ABC (or DEF, possibly even GH&I).

The unknown contributions of the Scotian Shelf (4WX), Gulf of Maine, and Georges Bank stocks can affect the stocks vulnerability to becoming overfished. For example, if the Scotian Shelf stock is contributing a significant amount of fish and that contribution decreases, the vulnerability to overfishing would increase. The vulnerability of the stock has been demonstrated by the historical collapse of the Georges Bank component in the 1980s, which also demonstrated that the multiple spawning groups can be differentially impacted by fishing. Varying contributions from the Scotian Shelf (4WX) stock may also contribute to a retrospective pattern (see below).

In the short-term, the relatively poor recruitments in 2013-2017 will increase the vulnerability of the stock to becoming overfished. The 2016 and 2017 cohorts were imprecisely estimated and so estimates of these cohorts may change significantly in either direction in future assessments, and decisions should likely consider this uncertainty. Growth (i.e., weight at age) also continues to be relatively low when compared to the 1990s, and this seems to be a longer-term feature of the stock that also reduces production. The stock, however, seems to be capable of producing relatively large and small year classes regardless of growth, and so recruitment is likely the more significant driver of short-term vulnerability.

While this assessment had a retrospective pattern that did not warrant adjustments (i.e., via Mohn's Rho), the history of the Atlantic herring stock assessment suggests that resolutions to retrospective patterns are ephemeral (NEFSC 2012; Deroba 2015). Given concerns that estimating catchability separately for the Bigelow years in 2009-2017 may also be aliasing other causes of the retrospective pattern (TOR B2; TOR B4), a safe assumption is that future herring assessments will have worsening retrospective patterns. Retrospective patterns are indicative of model misspecification, and this would increase the vulnerability of the stock to becoming overfished.

TOR B8: *If possible, make a recommendation about whether there is a need to modify the current stock definition for future assessments.*

Previous assessments (NEFSC 2012) concluded that there is likely sub-stock structure unaccounted for in the assessment, but that there is no ability to distinguish mixed survey and fishery catches to stock of origin. This lack of information on stock of origin precludes accounting for the sub-stock structure. In this assessment, a Stock Synthesis model was attempted (Appendix B4) that accounted for stock structure on a coarse level (i.e., Inside Gulf of Maine and Outside Gulf of Maine). In order to attempt this, however, assumptions were required that were likely incorrect, and model diagnostics were poor. The consequences of not accounting for stock structure are unclear, and therefore the need to modify the stock definition is also unclear. More certain, however, is that changing the stock definition and accounting for stock structure in the assessment is currently not possible. Continued research on the topic is warranted (see TOR B9).

TOR B9: *For any research recommendations listed in SARC and other recent peer reviewed assessment and review panel reports, review, evaluate and report on the status of those research recommendations. Identify new research recommendations.*

2018 Atlantic Herring Research recommendations:

- Further research on the use of acoustic technology for inclusion in stock assessment, including information using industry based platforms. Specifically:
    - Investigate methods for converting herring acoustic indices to biomass.
    - Investigate refinements in target strength conversion to abundance estimates in acoustic data
    - Evaluate statistical design implications in acoustic data from surveys and ships of opportunity.
    - Additional research to better understand species identification using acoustic signals
- Investigate use of length data, stock structure and movement within assessment models (e.g. SS3)
- Evaluate data collected in study fleet program for informing assessment data. Development research ideas that can be addressed within the context of the study fleet.
    - Explore fisheries selectivity in greater depth. Perhaps with study fleet and with historical perspective with industry.
- Continue work related to understanding sources of variation in stomach contents, especially as this relates to the (GAMM) models used to develop an index of herring abundance.

General assessment recommendations:

- Develop a list of standards for evaluating data for possible use in stock assessment. Also develop standards for evaluating model diagnostics and inclusion criteria of indices.
- Develop protocols for multi model inference to provide management advice from stock assessments based on NEFSC experience as well as other input (e.g. model averaging approaches).

- Develop simulations to evaluate diagnostics that are useful under different scenarios (e.g. use of likelihoods, retrospective patterns for diagnostics, etc.).

2012 SARC Research Recommendations

a. *More extensive stock composition sampling including all stocks (i.e. Scotian Shelf).*

No additional work completed

b. *Develop (simple) methods to partition stocks in mixed stock fisheries.*

No simple methods completed. Work ongoing using SS3 model to address mixed stock issue.

c. *More extensive monitoring of spawning components.*

Work completed at NEFSC examining extended spawning season in a subset of the mixed stock. Egg survey data analyzed for use as SSB index.

d. *Analyze diet composition of archived mammal stomachs. Improve size selectivity of mammal prey. Also sea birds.*

No work completed for assessment however additional information added to recent herring MSE.

e. *Consider alternative sampling methods such as HabCam.*

No additional work completed.

f. *Research depth preferences of herring.*

Evaluation attempted using Study Fleet information but data incomplete for such analysis.

g. *Simulation study to evaluate ways in which various time series can be evaluated and folded into model.*

On-going work under SEAGRANT funding to Essington and Deroba.

h. *Evaluate use of Length-based models (Stock Synthesis and Chen model).*

SS3 initiated but needs additional work before consideration for use in assessment. Chen model no longer supported.

i. *Develop indices at age from shrimp survey samples.*

Average age-length key developed for application to survey samples. Will make request for a collection of age samples in shrimp survey.

j. *Evaluate prey field to determine what other prey species are available to the predators that could explain some of the annual trends in consumption.*

Some work done regarding sand lance but otherwise not completed.

k. *Develop statistical comparison of consumption estimates and biomass from model M.*

No additional work completed

l. *Consider information on consumption from other sources (i.e. striped bass in other areas) and predators inshore of the survey.*

No additional work completed

m. *Investigate why small herring are not found in the stomachs of predators in the NEFSC food habits database.*

No additional quantitative work completed, however discussions suggest a potential spatial mismatch between our survey coverage and small herring.

n. *Develop an industry-based LPUE or some other abundance index (Industry Based Survey).*

No additional work completed, however ongoing discussion regarding use of acoustic information collected by industry.

o. *Develop objective criteria for inclusion of novel data streams (consumption, acoustic, larval, etc) and how can this be applied.*

Criteria for inclusion already in place, although not completely documented. (see new recommendations).

2012 CIE Research Recommendations

1. *Alternative catch scenarios could be developed to account for uncertainty in the stock boundary, particularly including catches from the Scotian Shelf. This would also allow examination of whether catch underestimation (e.g. inclusion of Scotian shelf catch) can contribute to the reduction in the retrospective pattern and contribute to or explain the need for increased M.*

No additional work completed

2. *Look at the effect of adding a penalty to encourage the NMFS survey trawl door-change q ratios to be similar in spring and fall.*

No indication based on calibration experiment that this is necessary.

3. *Using simulation/estimation methods, evaluate consequences of alternative harvest policies in light of uncertainties in model formulation, presence of retrospective patterns, and incomplete information on magnitude and variability in M (see term of reference 9).*

Considered to some extent in recent MSE work.

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B. Atlantic Herring – List of appendices

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Appendix B2 - A State-Space Stock Assessment Model (SAM) for Gulf of Maine – Georges Bank Atlantic Herring

Appendix B3 – Consideration of a model ensemble – model averaging ASAP and SAM (***coming soon***)

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Appendix B1.

Otolith exchange text.

Herring ageing: the history and recent exchanges

Jonathan J. Deroba, Eric Robillard, Gary Shepherd, Matt Cieri

Introduction

Estimates of abundance (biomass), fishing mortality (*F*), recruitment, and management quantities (e.g., recommended yield) can be biased when using age-based stock assessments with imprecise or biased age information (Bradford 1991; Eklund et al., 2000; Reeves 2003; Bertignac and Pontual 2007; Yule et al., 2008). Imprecise ageing can cause estimates of abundance or *F* to be biased in scale, but not necessarily trend, while recruitment estimates may be biased in scale and falsely autocorrelated (Bradford 1991; Reeves 2003). Biased age information can cause estimates of abundance, *F*, and recruitment to be biased in scale and trend, and result in inappropriate catch and management advice (Bradford 1991; Eklund et al., 2000; Reeves 2003; Bertignac and Pontual 2007; Yule et al., 2008).

Atlantic herring *Clupea harengus* in the northwest Atlantic Ocean have been assessed using age-based stock assessment models (Anthony 1977; NEFSC 1993; NEFSC 1998; Overholtz et al., 2004). The age-based assessments rely on ages from multiple agencies. Commercial catch samples are aged by the Canadian Department of Fisheries and Oceans (DFO) and the Maine Department of Marine Resources (DMR). Survey catch samples are aged by the US National Marine Fisheries Service (NMFS). Periodic evaluations of the accuracy and precision of herring ageing, however, have revealed disagreements among ageing labs and potential biases (Dery and Chenoweth 1979; Overholtz et al., 2004; Libby et al., 2006). Results of an otolith exchange among agencies conducted during the 2003 stock assessment suggested that age readers from DMR and NMFS were generally in agreement, except for about a 10% difference for fish older than about age-4, with the NMFS reader concluding that fish were younger (“underageing”) than the DMR reader (Overholtz et al., 2004). Significant differences of greater than 50% at some older ages were found between the DFO lab and both US facilities, with the DFO concluding that fish were younger than both US readers. An ageing workshop and second otolith exchange were conducted in 2006 (Libby et al., 2006). Generally, agreement among the ageing labs in the second otolith exchange was worse than during the 2003 assessment. Age readers from DMR and NMFS agreed 54% of the time and DMR tended to conclude that fish were younger than NMFS, which is the reverse of the discrepancies found in 2003. Age readers from DFO and NMFS agreed only 39% of the time and DFO generally concluded that fish were younger than NMFS. Similarly, DFO and DMR agreed 58% of the time, with DFO concluding that fish were younger than DMR.

While otolith exchanges provide information on ageing precision and differences among labs, they do not inform accuracy. Using bomb radiocarbon dating to evaluate herring ageing accuracy, Melvin and Campana (2010) concluded that herring aged six and older were often underaged, while ages of younger fish were relatively well determined. The inaccuracy of ageing for older fish is consistent with the results of the otolith exchanges that also found greater disparity at older ages. Since 2003, DFO and DMR have re-aged much of their historical catalogue using techniques agreed to during ageing workshops (Libby et al., 2006), but concerns about herring age accuracy and precision have lingered (NEFSC 2012).

During the 2012 Atlantic herring stock assessment, systematic differences were found between age-length keys (ALKs) from commercial samples aged by the DMR and survey samples aged by NMFS (see below; NEFSC 2012). One possible explanation for these differences is ageing errors. This manuscript describes work that has been done since 2012 to evaluate the potential for ageing errors in the Atlantic herring stock assessment.

Methods

Examinations of ageing data

Prior to the 2012 stock assessment, ALKs for herring from commercial and survey samples were combined to eliminate lengths for which no age data were available (i.e., “fill holes”), increase sample sizes and precision, and allow for survey age compositions to extend prior to 1987, the year when ages were first sampled for herring during NMFS surveys. Combining ALKs among gears, spatial areas, and time, however, can induce bias in the subsequent age compositions and stock assessments (Westrheim and Ricker 1978; Quist et al., 2012; Gerritsen et al., 2006). During the 2012 stock assessment, the practice of combining ALKs from commercial and survey sources was evaluated by plotting the proportion of fish at length assigned to each age by the commercial mobile gear fishery ALK in the first semester of each year (i.e., January-June) with the NMFS spring survey ALK for each year from 1987-2010 (NEFSC 2012). Using only commercial gear samples from the first semester of the year was intended to control for growth within the year that might affect the ALKs. These plots were then visually compared, with general consistency suggesting that ALKs could likely be combined, and inconsistency suggesting that ageing error or some other issue may be problematic and ALKs should not be combined. Consistency between the DMR and NMFS ageing labs was evaluated by plotting the mean age in 5cm length bins in each year estimated from samples collected from the commercial mobile gear fishery in the first semester of each year with mean age estimated using NMFS spring survey samples. The same plots were created using samples collected from the commercial mobile gear fishery in the second semester of each year and the NMFS fall survey. Similarly, samples from all years were combined and mean age in 1 cm length bins was estimated from samples collected from the commercial mobile gear fishery in the first semester and plotted with mean age estimated using NMFS spring survey samples, and a similar plot was created using samples collected from the commercial mobile gear fishery in the second semester of all years and the NMFS fall survey. These plots were visually compared, with consistency suggesting no evidence of ageing error, but systematic differences suggesting the opposite conclusion.

Recent otolith exchanges

To make sure that all labs providing ages followed the same protocols, otoliths exchanges between labs occurred in 2014, 2016 and 2017. The following measures were used to characterize the results of tests of ageing consistency between the labs:

Coefficient of Variation (CV)

The mean coefficient of variation (CV, Campana *et al*. 1995, Chang 1982) is a relatively robust approach to quantifying agreement in fish ages. It yields results which are easier to compare between species and structures. Also, the contribution each fish makes to the CV is relative to the average age assigned to that fish; i.e., a 2-year error in ageing a young fish would increase the measure more than would a 2-year error in an older fish, as the percentage change in age is greater for younger ages.

The CV is based on the differences between the mean age and each given age for each fish, and then these values are averaged over the entire sample set. When two ages are assigned to each fish, the CV is calculated as follows:

$$CV = 100\% \times \frac{1}{N} \sum_{j=1}^{N} \frac{\sqrt{\sum_{i=1}^{2} (X_{ij} - X_j)^2}}{X_j}$$

where X_{ij} is the *i*th age for the *j*th fish, X_j is the mean age of the *j*th fish, and N is the sample size. Campana (2001) indicates that many ageing laboratories around the world view CVs under 5% to be acceptable among species of moderate longevity and ageing complexity. His description applies to all the herring exchanges that have occurred since 2012.

Percent Agreement

The Fishery Biology Program has used this measure since the group's inception, and considers levels of over 80% to be adequate. It is calculated based on the percentage of ages agreed upon relative to the total number aged:

$$\text{Percent Agreement} = 100 \times \frac{\text{Number of agreements}}{N}$$

For this measure, an error in ageing a young fish changes the measure by the same amount as would a similar error for an old fish. Therefore, this statistic is harder to compare between samples sets with different age distributions.

Bowker's Test of Symmetry

For both types of precision test, a Bowker's test (Hoenig *et al.* 1995, Bowker 1948) was used to test for departures from symmetry within the age-frequency table. Such asymmetries indicate the presence of a bias, although the test has low sensitivity when few disagreements exist. Where ages differ from one another, the Bowker's test compares values on the age-frequency table which represent symmetric errors, such as the paired ages (3,4) and (4,3). If all such values are dissimilar, the test will return a significant P value.

This test statistic is calculated as a chi-square variable, as follows:

$$\chi^2 = \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} \frac{(n_{ij} - n_{ji})^2}{n_{ij} + n_{ji}}$$

where m is the maximum age in the data set, and n_{ij} is the number of fish in the *i*th row and *j*th column (Hoenig *et al.* 1995, Bowker 1948). The value of the degrees of freedom is equal to the number of non-zero n_{ij}-n_{ji} comparisons in this calculation, to a maximum of m(m-1)/2.

Results

Examinations of ageing data

All plots of the proportion of fish at length assigned to each age for each year can be found in NEFSC (2012), and so only example plots were provided here. The proportion of fish at length assigned to each age was generally similar between the commercial mobile gear fishery ALK in the first semester of the year and the NMFS spring survey ALK from 1987-1992 (Figure 1-top). The proportion of fish at length assigned to each age was also similar for ages 1-2 during 1993-2010 (Figure 1-bottom). For ages 3 and older, however, the NMFS spring survey ALK generally assigned a larger proportion of fish to each age at smaller lengths and a smaller proportion of fish to each age at larger lengths than the commercial mobile gear fishery ALK during 1993-2010 (Figure 1-bottom).

Mean ages in 5cm length bins were generally similar for the DMR mobile commercial samples and NMFS spring and fall survey samples for the 15-19cm and 20-24cm bins (Figure 2). The exception was between the DMR mobile commercial samples from the second semester and the NMFS fall survey for the 15-19cm length bin during 1987-1991, when the NMFS fall survey mean ages were approximately one year less than the DMR samples (Figure 2).

Mean ages in 5cm length bins differed for the DMR commercial samples and the NMFS spring and fall survey samples for the 25-29cm and 30-35cm bins, and the differences trended among years (Figure 3). Although the severity of differences and trends varied among length bins and seasonal surveys, some patterns were similar. Mean age from the NMFS surveys were less than the mean ages from commercial samples from 1987 until the mid-1990s, similar from the mid-1990s to the early 2000s, and greater than the commercial samples for the remainder of the time series (Figure 3).

Mean ages in 1cm length bins for all years combined (1987-2013) were similar from the smallest bins until about 28cm, after which the survey mean ages were about 1-3 years less than the DMR commercial samples (Figure 4). Mean ages from the DMR commercial samples increased relatively smoothly with length, as might be expected from a von Bertalanffy growth curve, whereas the mean ages from the surveys suggested an irregular increase in age with length beginning at about age-6 (Figure 4).

Recent otolith exchanges

Following Campana's 2001 recommendations, ageing labs around the world consider to have acceptable ages if there is 80% or higher agreement and a CV of 5 % and under. All herring exchanges between the labs fit in this category, with had high percent agreement with low variation (figure 5). Of the seven exchanges, only one had a 73.3% agreement but the CV still met the standard with 3.72%. The average agreement and CV between the 7 exchanges was 83.78% and 2.1% respectively. Bowker's test showed there was a bias between DFO and NEFSC in 2014 and between Maine and NEFSC in 2016. There seemed to be no pattern to the bias has it was two different labs, and were followed by other exchanges in which the bias did not show up.

Conclusions

Results suggest some systematic differences between commercial and survey ages. Consistency among DMR and NMFS ageing labs was also worse for larger and older fish (Figures 1-4), which was consistent with results from previous ageing workshops on herring (Overholtz et al., 2004; Libby et al., 2006) and the work of Melvin and Campana (2010). Results also suggest that the severity of the problem, be it ageing error or some other source, may vary through time. The comparison of the ALKs from commercial and survey sources (Figure 1) and mean age in various length bins (Figures 2-3) show temporal trends. The plots of mean age in various length bins suggest greater ageing discrepancies from about 1987 to the mid-90s, better agreement from the mid-90s to mid-00s, and increased discrepancies in recent years.

This research cannot definitively conclude that ageing error or differences in ageing methods is a problem, but other explanations for the patterns in the data seem unlikely. One alternative is that cohorts of herring school independently of each other, such that the mean age at length of fish from one school would differ from the mean age at length of catch from another school. For this to be a valid explanation, however, the pattern of mean age in 1cm length bins (Figure 4) would require that the NMFS randomized survey systematically misses schools from older cohorts, while a commercial fishery targets schools of older fish. This explanation is unlikely, especially considering that schools of older fish would likely be smaller than schools of younger fish, and therefore inefficient for the fishery to target. This age-based segregation has also never been observed in Atlantic herring in this area. The NMFS survey catches could be detecting signals from cohorts outside of the Georges Bank/Gulf of Maine complex. This explanation, however, is also unlikely because the confounding in the signal does not seem to start until older ages and the fishery operates over much of the same area as the NMFS surveys.

Results of recent otolith exchanges suggest consistent aging methodologies and generally trustworthy ages, regardless of source. Ultimately, combining ALKs from different sources should be abandoned for Atlantic herring, especially in previous years where no explanation is available for discrepancies in the data.

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Figure 1. The proportion of fish at length assigned to each age using the commercial mobile gear fishery ALK from semester one of each year (black line) and the NMFS spring survey ALK (red line) in 1988 (top) and 1997 (bottom).

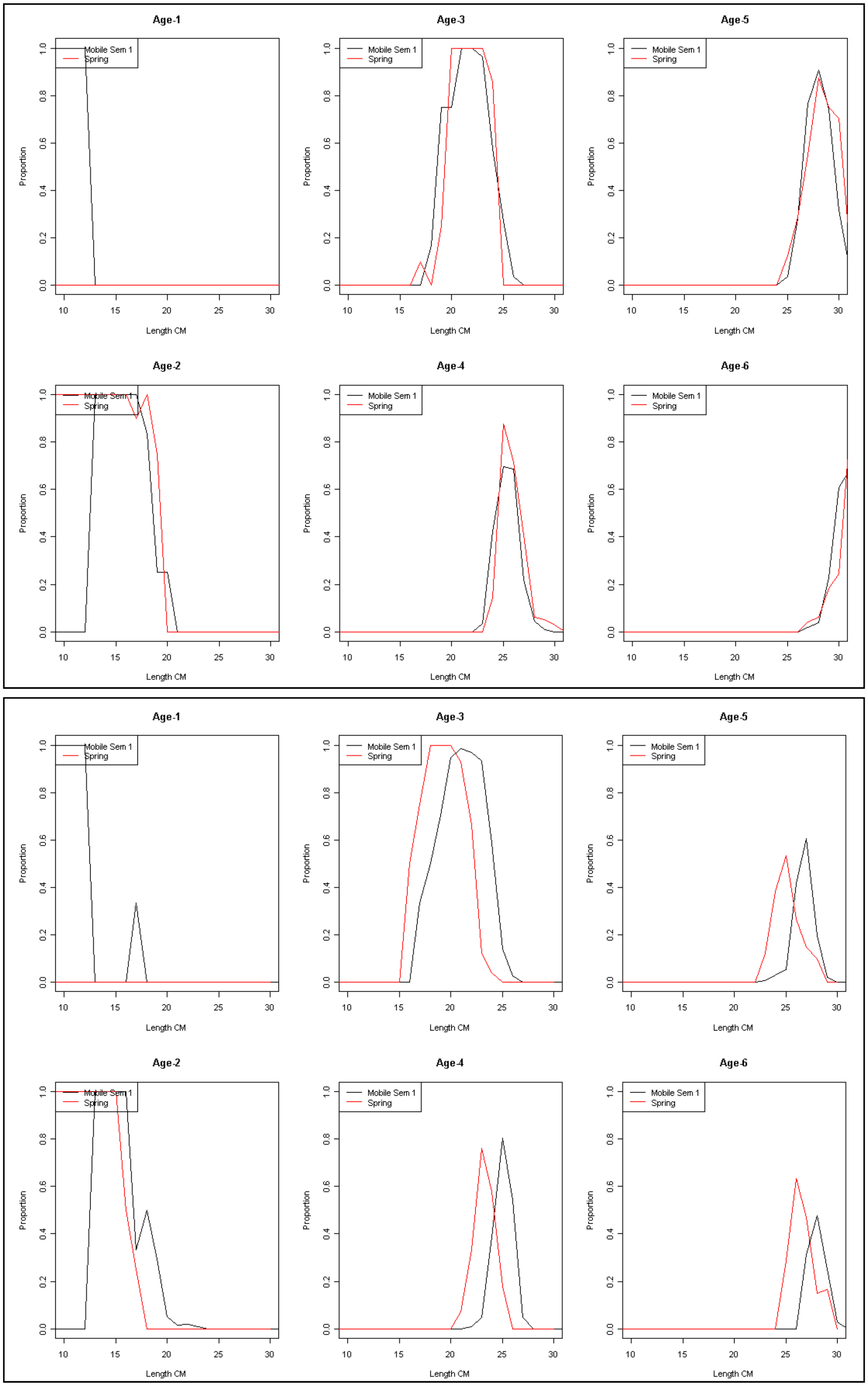
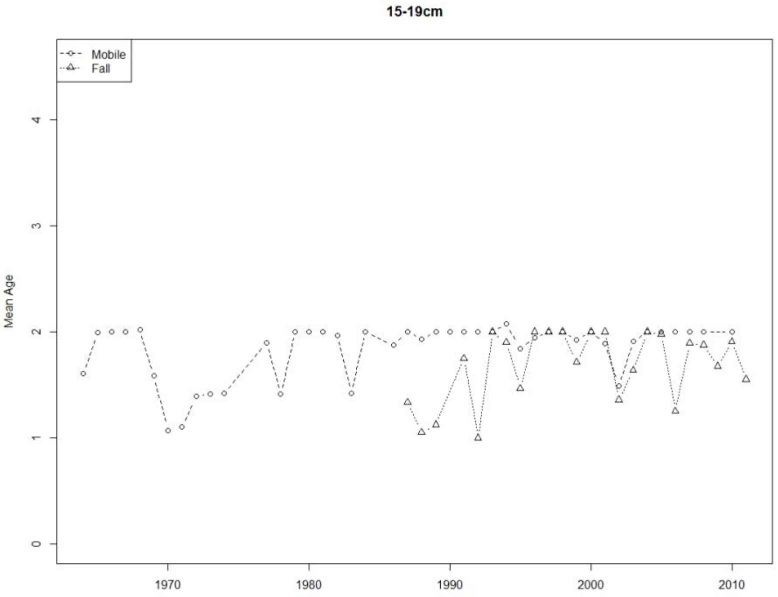
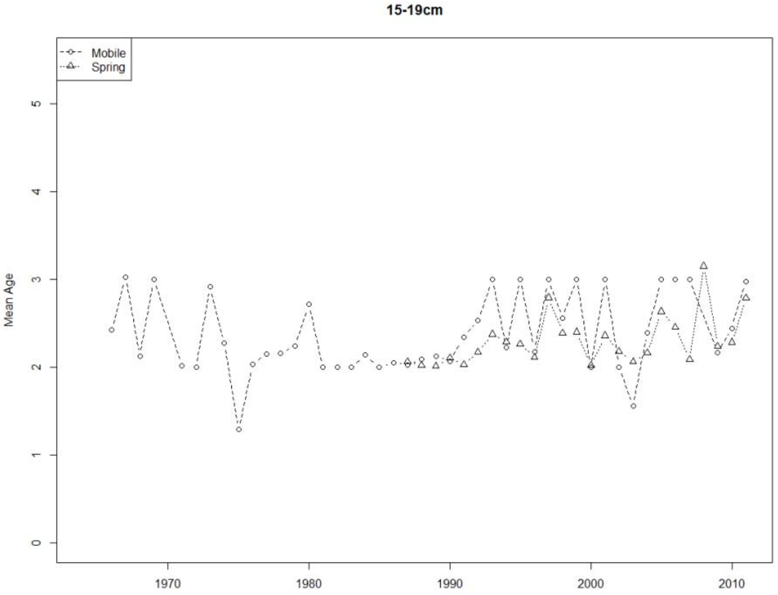
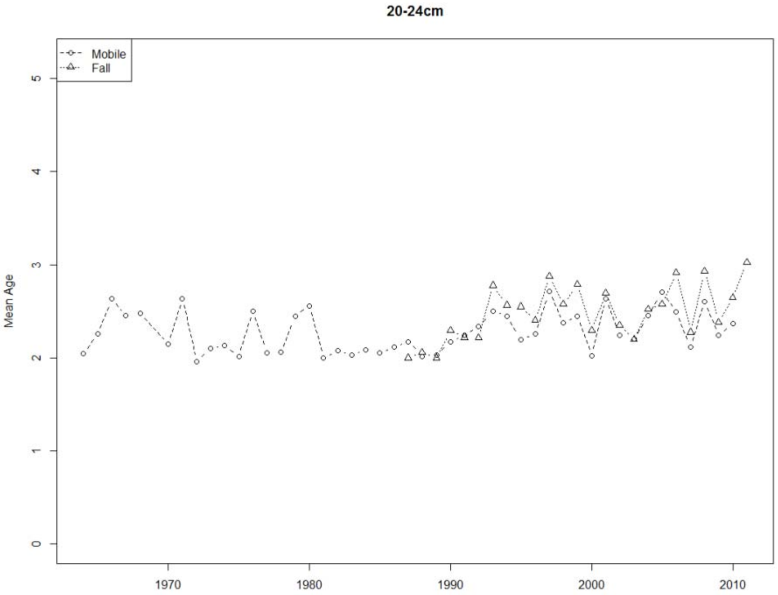


Figure 2. Mean age of herring in 5cm length bins for mobile commercial samples from semester one of each year and NMFS spring survey samples or mobile commercial samples from semester two of each year and NMFS fall survey samples during 1987-2011.






20-24cm
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2000
2010

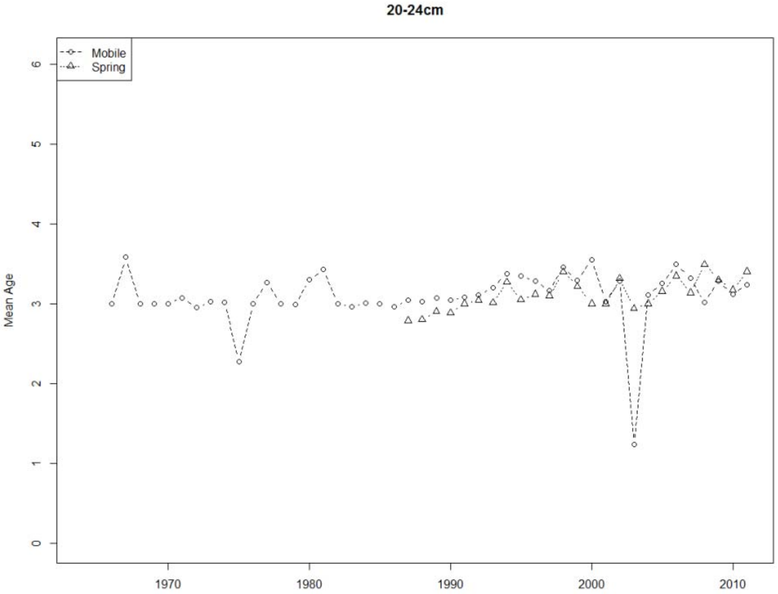
20-24cm
Mobile
Spring
Mean Age
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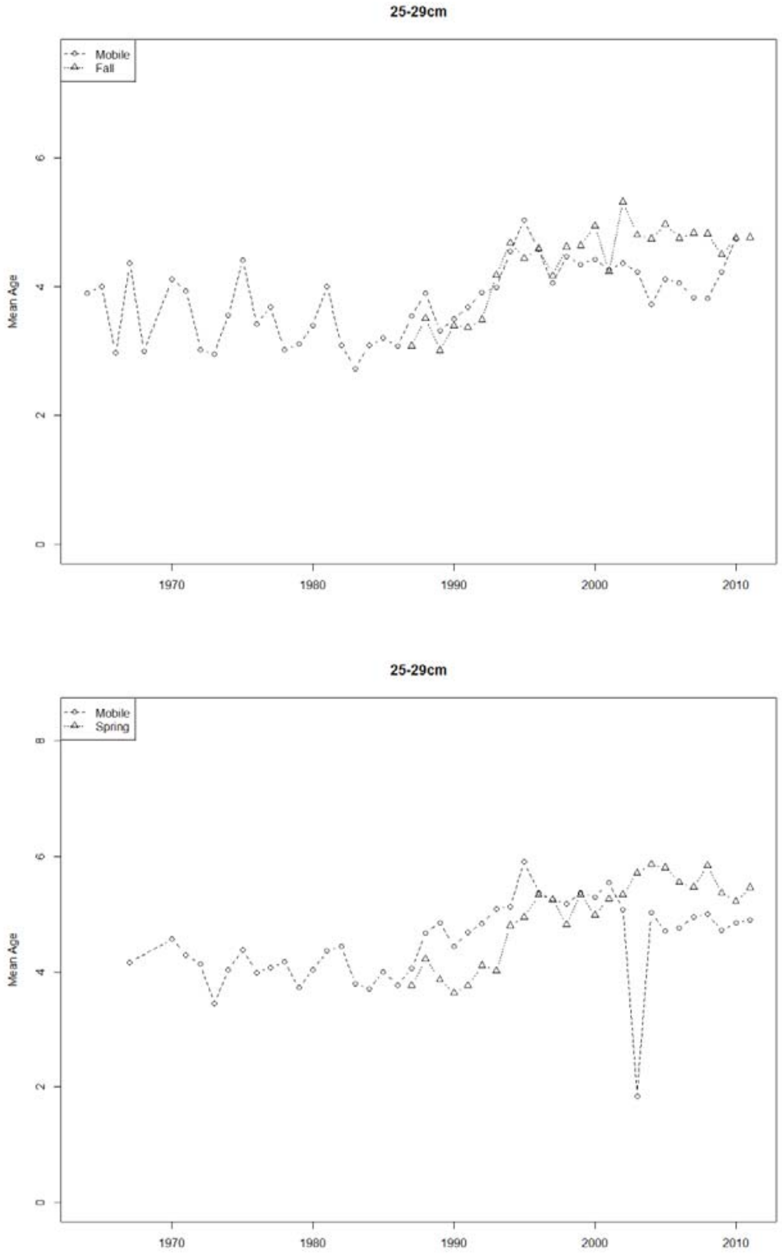
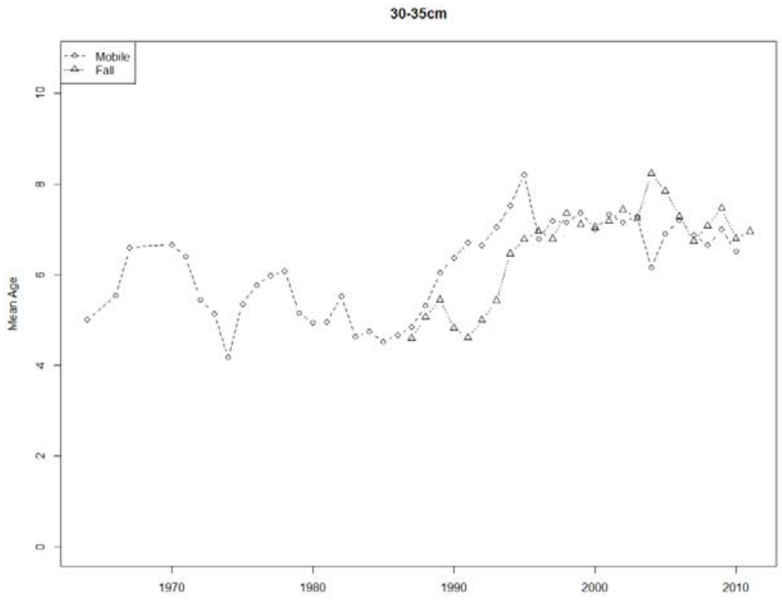
Figure 3. Mean age of herring in 5cm length bins for mobile commercial samples from semester one of each year and NMFS spring survey samples or mobile commercial samples from semester two of each year and NMFS fall survey samples during 1987-2011.




30-35cm
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Mean Age
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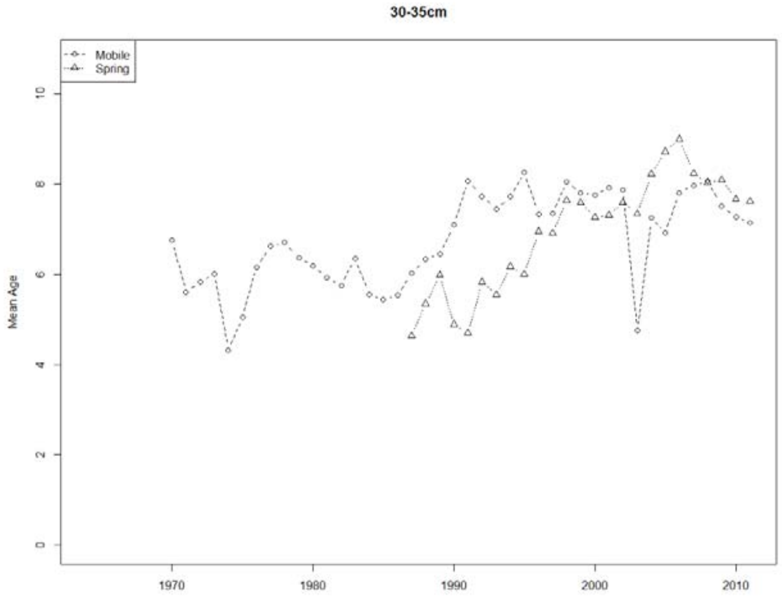
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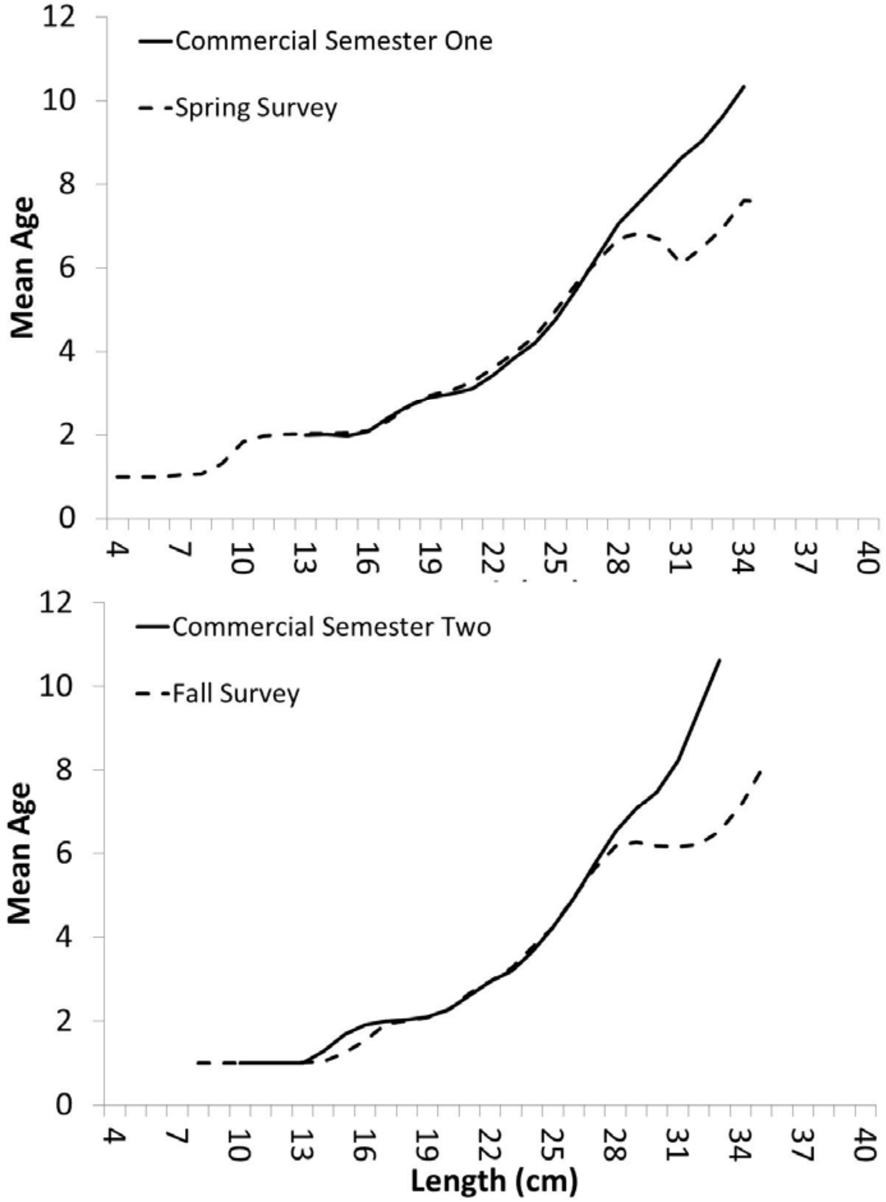
Figure 4. Mean age of herring in 1cm length bins for mobile commercial samples from semester one and NMFS spring survey samples or mobile commercial samples from semester two and NMFS fall survey samples for all years combined from 1987-2013.



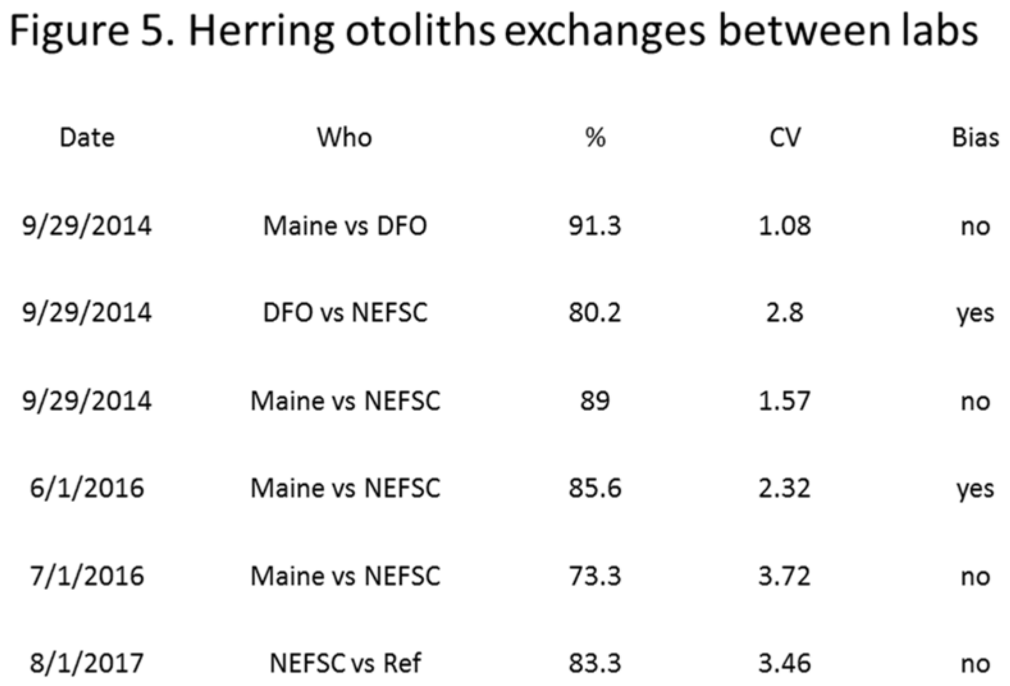


Figure 5. Herring otoliths exchanges between labs

Date	Who	%	CV	Bias
9/29/2014	Maine vs DFO	91.3	1.08	no
9/29/2014	DFO vs NEFSC	80.2	2.8	yes
9/29/2014	Maine vs NEFSC	89	1.57	no
6/1/2016	Maine vs NEFSC	85.6	2.32	yes
7/1/2016	Maine vs NEFSC	73.3	3.72	no
8/1/2017	NEFSC vs Ref	83.3	3.46	no

Appendix B2

A State-Space Stock Assessment Model (SAM) for Gulf of Maine – Georges Bank Atlantic Herring

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Introduction

Fish stock assessments rely on observations (e.g., survey indices, catch, age composition) to inform fishing, survival, and reproduction processes (e.g., fishing mortality, selectivity). The observations and the processes are both subject to error. Observations are collected through sampling procedures that are subject to measurement error, while some processes like selectivity and survival are not directly observed and so are subject to process errors not reflected in the observed data.

Stock assessment approaches vary in the degree to which observation and process errors are acknowledged. Virtual population analyses do not allow any observation or process errors because data are assumed perfectly known. Statistical catch-at-age (SCAA) models permit observation errors and limited process error in recruitment, but the extent of the errors are user specified and the models estimate relatively many parameters (e.g., a fishing mortality rate and recruitment for each year). State-space models can separate observation and process errors using relatively few parameters (Nielsen and Berg 2014). This efficiency is achieved by estimating the variances of the assumed distributions for the observation and process errors, and the fishing mortality and abundance states are predictions from the assumed distributions, as opposed to free parameters as in SCAA models.

The objective of this working document was to apply a SAM model to Gulf of Maine – Georges Bank Atlantic herring. I provide an overview of the model here, but details can be found in Nielsen and Berg (2014) and Berg and Nielsen (2016). Notation generally follows that of Nielsen and Berg (2014).

Methods

Observations

Catch and index observations are assumed to have lognormal errors, with separate variance parameters applied to different user selected age groups:

$$\log\left(C_{a,y}\right) = \log\left(\frac{F_{a,y}}{Z_{a,y}}(1 - e^{-Z_{a,y}})N_{a,y}\right) + e_{a,y}^{(o)} ;$$

$$e_{a,y}^{(o)} \sim N\left(0, \hat{\sigma}_{o,a}^{2}\right) ;$$

$$\log\left(I_{a,y}\right) = \log\left(\hat{q}N_{a,y}\right) + e_{a,y}^{(s)} ;$$

$$e_{a,y}^{(s)} \sim N\left(0, \hat{\sigma}_{s,a}^{2}\right) .$$

Age groups were defined to share variance parameters based on AIC and residual patterns.

Processes

SAM allows for process errors in recruitment, survival between sequential ages, and age specific fishing mortality rates. The recruitment and survival processes are assumed to follow lognormal distributions:

$$\log\left(R_{a=1,y}\right) = \log\left(f\left(SSB_{y-1} \; or \; R_{a=1,y-1}\right)\right) + \gamma_{a=1,y} ;$$

$$\gamma_{a=1,y} \sim N(0, \hat{\sigma}_{R}^{2}) ;$$

$$\log\left(N_{a,y}\right) = \log\left(N_{a-1,y-1}\right) - F_{a-1,y-1} - M_{a-1,y-1} + \gamma_{a>1,y} ;$$

$$\gamma_{a>1,y} \sim N(0, \hat{\sigma}_{a>1}^{2}) .$$

Recruitment in all model runs was assumed to follow a random walk. As with the observation variances, age groups were defined to share survival process variance parameters based on AIC and residual patterns.

Fishing mortality rates can be age-specific or groups of ages can be coupled to share fishing mortality rates, and these rates follow a random walk between years. The random walk fishing mortality rates can be correlated among the age couplings, for example, with a correlation of 0.0 producing independent random walks among age couplings and a correlation of 1.0 producing parallel time trajectories in fishing mortality rates among age couplings (i.e., time invariant selectivity). This results in age- and year-specific random walk increments following a multivariate normal distribution:

$$\log(F_{a,y}) = \log(F_{a,y-1}) + \delta_y \,;$$

$$\delta_y \sim \boldsymbol{N}(0, \widehat{\boldsymbol{E}}) \,.$$

The degree of correlation in the random walks can be fixed at 0.0 (i.e., independent) or estimated, and both were attempted. Age groups were defined to share fishing mortality states and process variances based on AIC and residual patterns.

Input Data

The input data were similar to that used in the ASAP base model, but SAM can only fit to age-based indices or indices of SSB. That is, SAM cannot fit to annual, aggregate index observations with user specified selectivity. Consequently, the SAM model only fit to NMFS spring, fall, and summer (shrimp) bottom trawl surveys for the years 1987-2017. In summary, input data were:

- Catches-at-age for ages 1-8+, with age 8 as a plus group, for the years 1965-2018.
- The NMFS spring and fall bottom trawl surveys for ages 2-8+ from years that used the vessel Albatross, 1987-2008.
- The NMFS spring and fall bottom trawl surveys for ages 2-8+ from years that used the vessel Bigelow, 2009-2017.
- The NMFS summer (shrimp) bottom trawl survey for ages 2-8+ from 1987-2017.
- Natural mortality equaled 0.35 for all ages and years.
- Age- and year-specific maturity was the same as the base ASAP model, as were weights at age.

Results

More than 20 models were run in the development of the SAM model. Presenting the AIC values and diagnostic plots that led to the final model structure would be voluminous. Consequently, only the final model structure is described. Supporting figures are at the end of this document.

Observations

Two separate observation variances were estimated for fishery catches, one that applied to ages 1-6 and another applied to ages 7-8+.

The spring NMFS survey for the Albatross years had separate catchabilities for age 2, 3, 4-6, and 7-8+, and different observation variances for age 2, 3-6, and 7-8+. The fall NMFS survey for the Albatross years had separate catchabilities for age 2, 3, 4, and 5-8+, and different observation variances for age 2-6 and 7-8+. The spring NMFS survey for the Bigelow years had separate catchabilities for age 2, 3, 4, and 5-8+, and different observation variances for age 2-3, 4-8+. The fall NMFS survey for the Bigelow years had separate catchabilities for age 2, 3, 4-6, and 7-8+, and a single observation variance that applied to all ages. The summer NMFS survey had separate catchabilities for age 2, 3, 4, 5, 6, and 7-8+, and different observation variances for age 2, 3-7, and 8+.

Processes

Unique fishing mortality rates were specified for age-1, age-2, age-3, age-4, age-5, age-6, and ages 7-8+. The fishing mortality rates were assumed to follow independent random walks. A model that estimated the degree of correlation among the fishing mortality rates improved the model fit based on log-likelihood, but did not resolve any residual patterns and so this parameter was not estimated.

Separate process variances were estimated for the fishing mortality rates at age 1, 2-4, 5-6, and 7-8+. Process variance in recruitment was estimated separately from a survival process variance shared among ages 2-8+.

Summary of Final SAM Model Structure

- Two fishery catch observation variances (2 parameters).
- Eleven observation variances among all the surveys (11 parameters).
- 22 catchability parameters among all the surveys (22 parameters).
- Four fishing mortality rate process variances (4 parameters).

- Process variance for recruitment and a survival process variance for ages 2-8+ (2 parameters).
- 41 total parameters.

Overview of Final SAM Model Estimates and Results ("Run 13")

The time-varying fishing mortality rates suggested a generally flat-topped selectivity, with ages 7-8+ having the highest fishing mortality rates in most years and age 1 having the lowest selectivity in all years. The fishing mortality rates and subsequent selectivity at ages 2-6, however, were relatively variable. Age-2 had a relatively high selectivity in the 1970s due to higher catches from fixed gear sources during those years, but has since declined as mobile gears have become more dominant. Selectivity at other ages changes through time in a near parallel and cyclic manner.

Fishing mortality rates at age 1 had the largest of the process variances, followed by recruitment. Observation variances differed among ages and data sources.

The model did not exhibit a retrospective pattern. Fitting the model without each of the surveys resulted in time series that were withing the 95% confidence intervals of the base SAM model. Fits to the catch and survey observations varied by data source, with relatively few patterns visible for some inputs (e.g., spring Albatross years), but year effects evident for some surveys (e.g., summer survey). Process residuals did not have any obvious patterns.

Time series estimates of recruitment, fishing mortality rate, and biomass (abundance) were generally similar to the final ASAP run.

Maximum sustainable yield proxy reference points were calculated using similar methods as for the base ASAP model. More specifically, the 5-year average of life history traits from 2013-2017 (e.g., maturity, weights-at-age) were used to calculate $F_{40\%}$ as an F_{MSY} proxy. Given that selectivity varies through time in the SAM model, the selectivities at age from 2013-2017 were also averaged for purposes of reference point calculation. Consequently, the $F_{40\%}$ value is not identical to that produced by the base ASAP model, nor is the corresponding B_{MSY} proxy. The B_{MSY} proxy was determined for the

SAM model by conducting a 50 year projection at $F_{40\%}$, which was of sufficient length for the projection to reach equilibrium. Projected recruitments each year were resampled from the full time series of recruitment estimates from the SAM model. Various aspects about how process variance is carried forward in projections for the SAM model were not clear to the Working Group, and best practices for reference point calculation from a state-space model have not been developed. Consequently, the reference points and stock status from the SAM model should be used only for informational purposes and not considered for use in management. The $F_{40\%}$ MSY proxy equaled 0.39 and the corresponding B_{MSY} proxy equaled 197,000mt. Based on the SAM model, the stock is overfished and overfishing is occurring. Measures of uncertainty about stock status, however, were not readily available, but the uncertainty would likely be larger than that from the ASAP model due to the inclusion of process errors in SAM.

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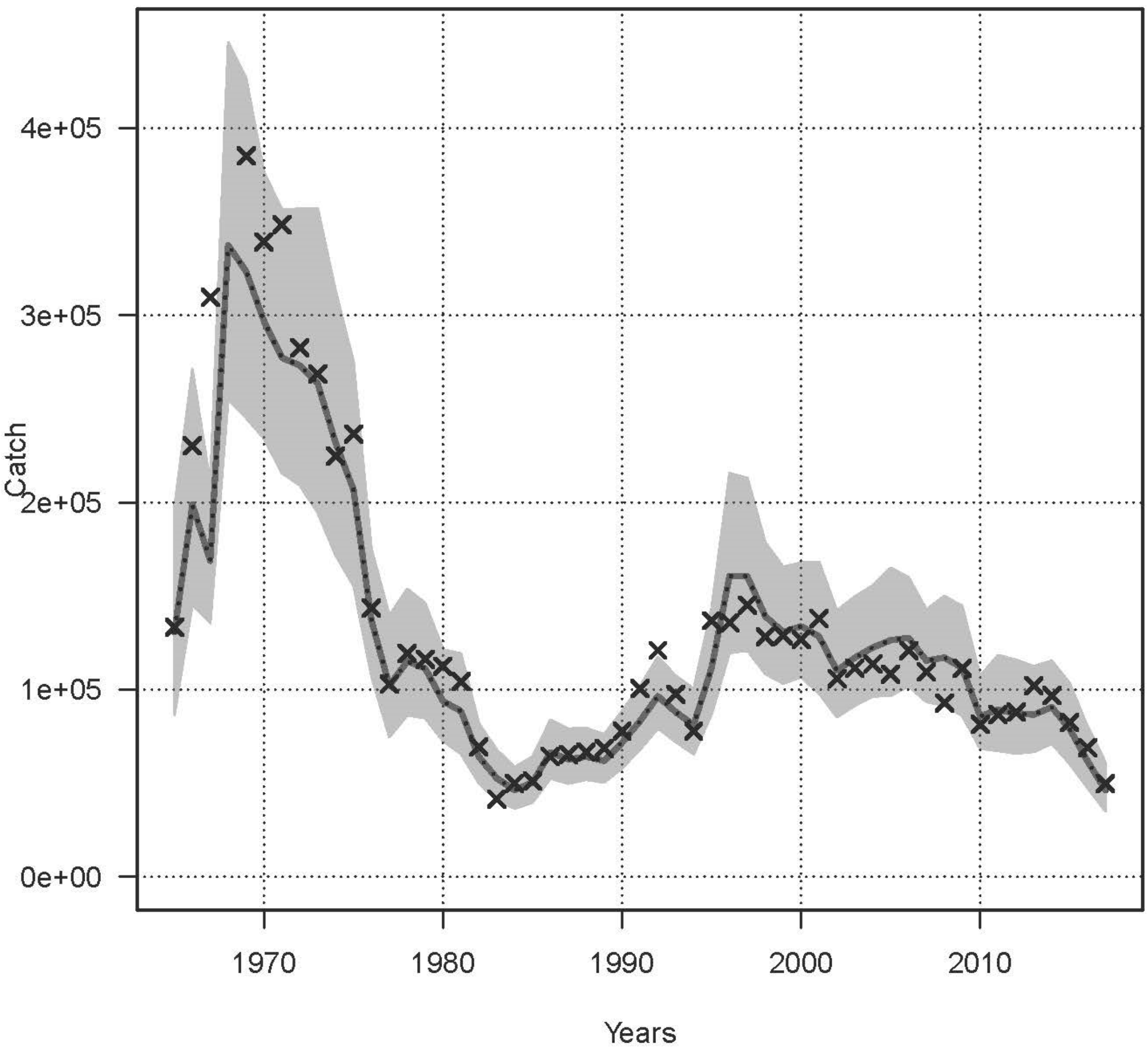
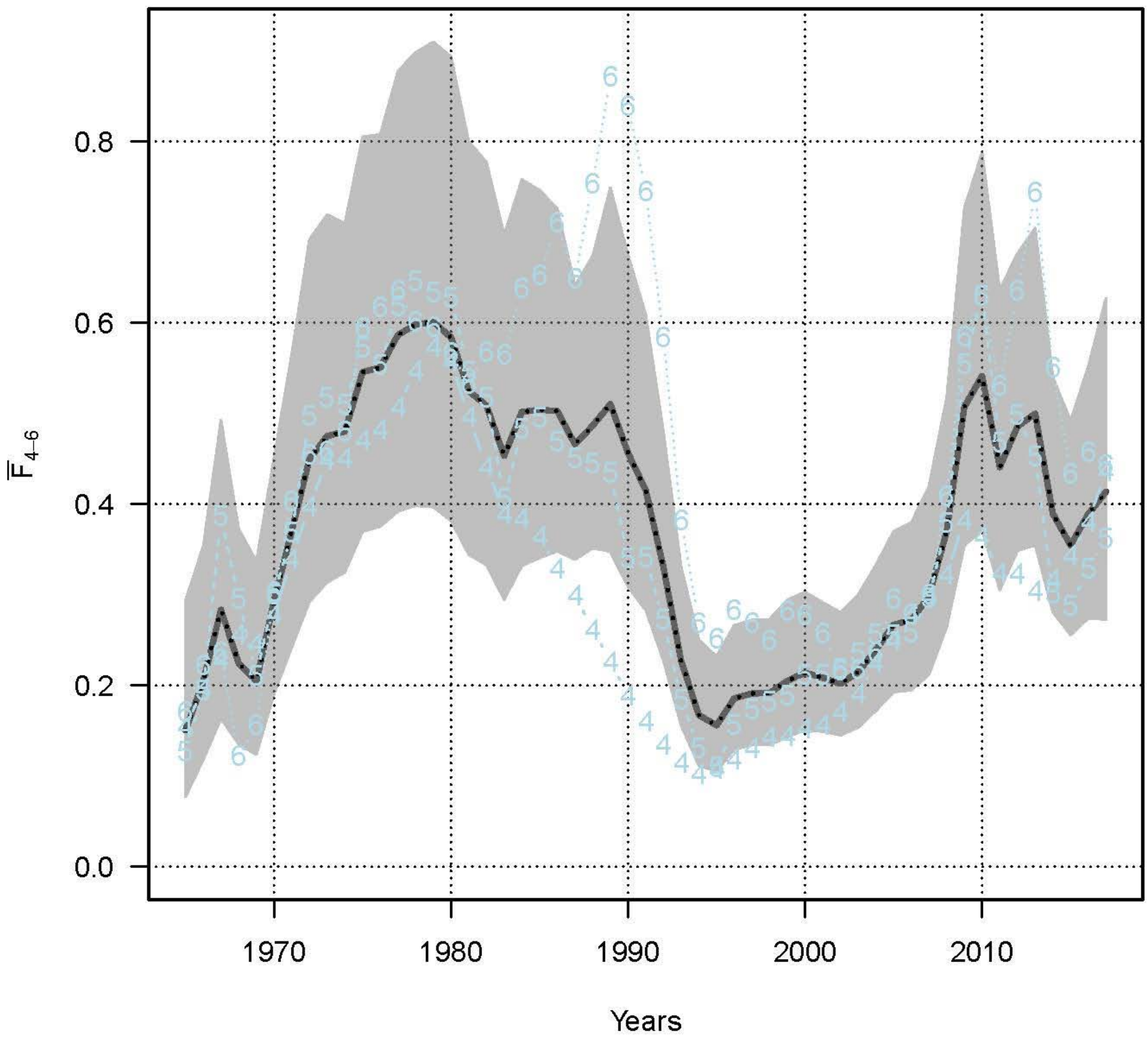
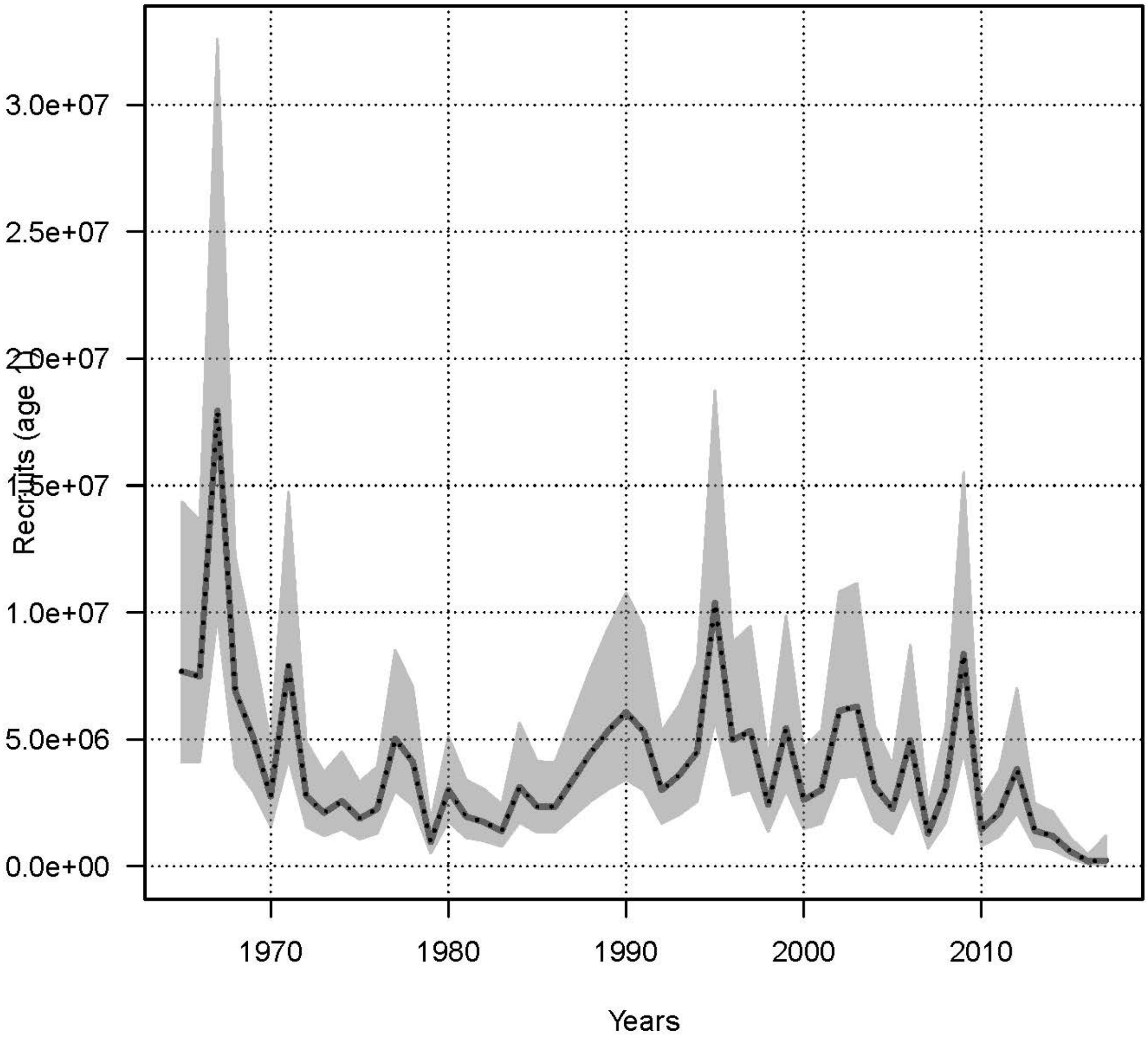
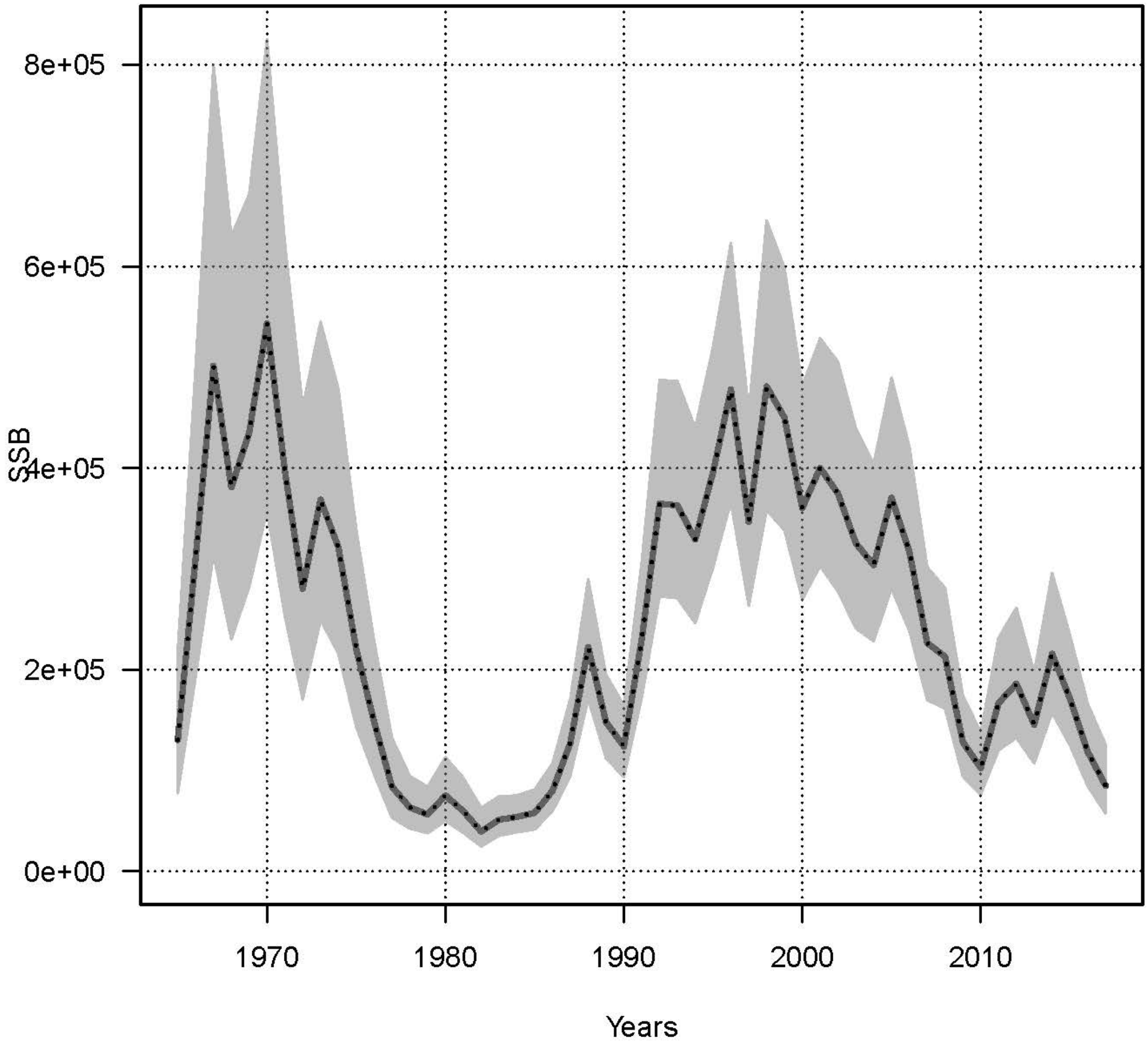
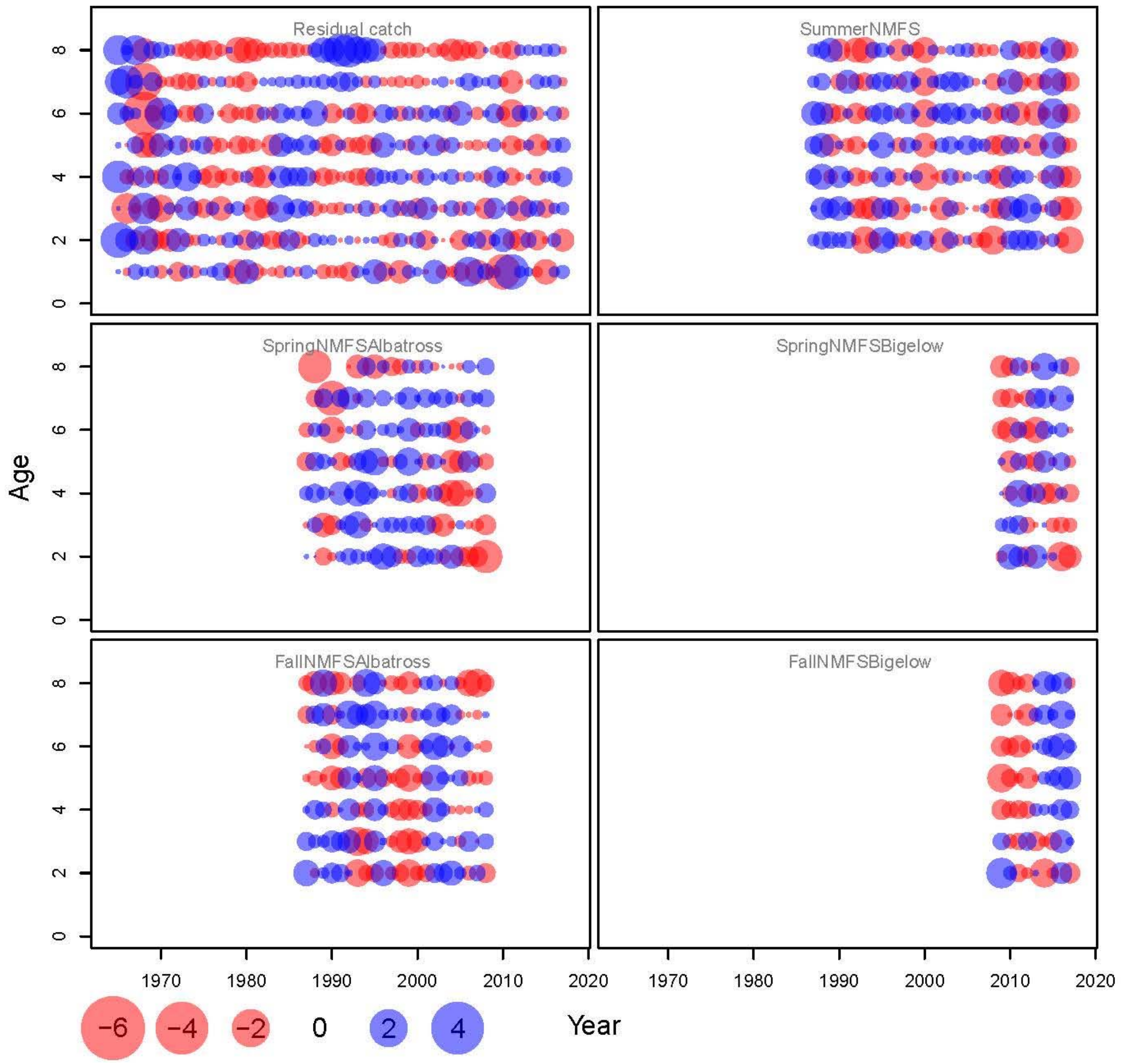
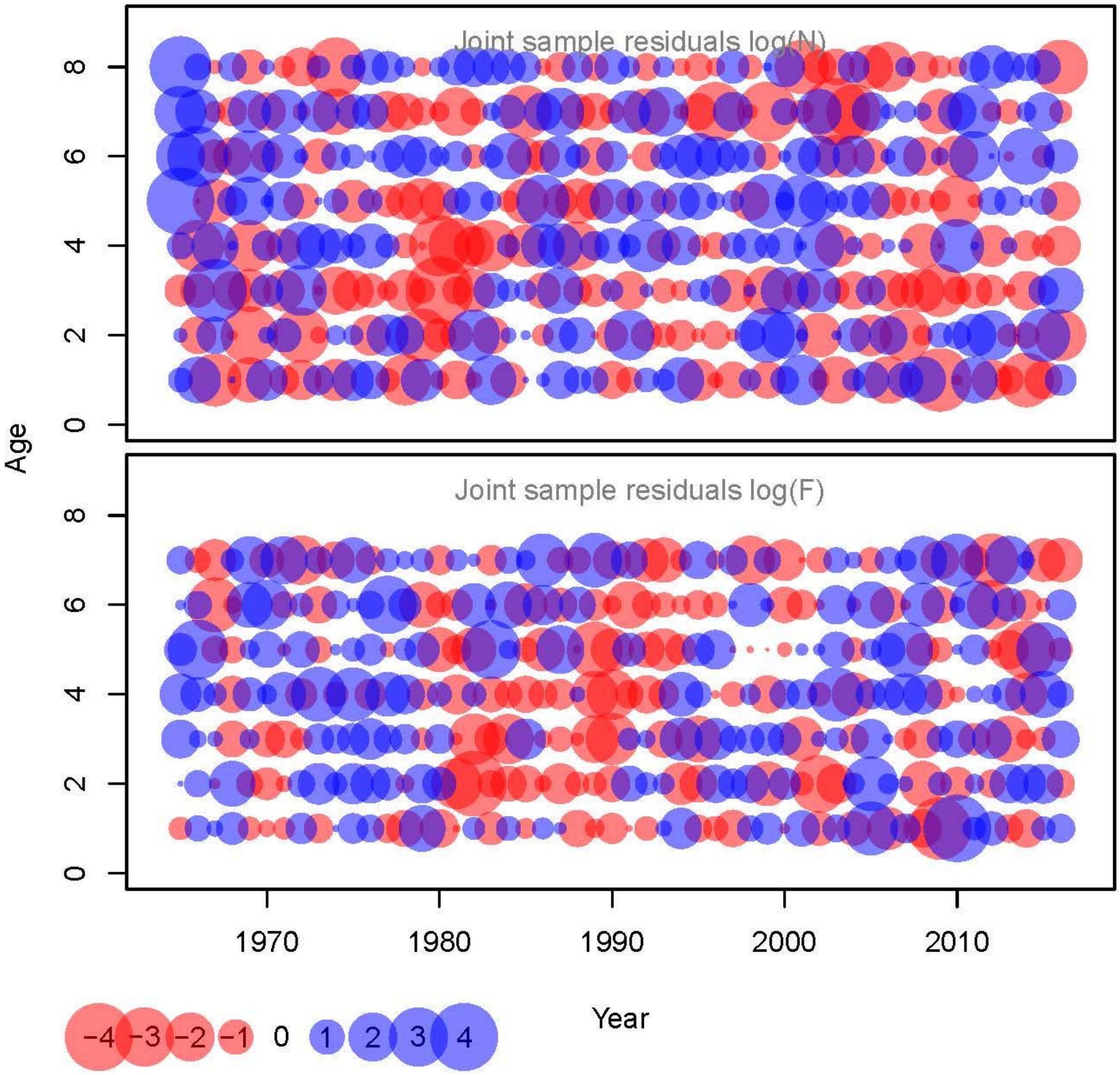

Catch
4e+05
3e+05
2e+05
1e+05
0e+00
1970
1980
1990
2000
2010
Years

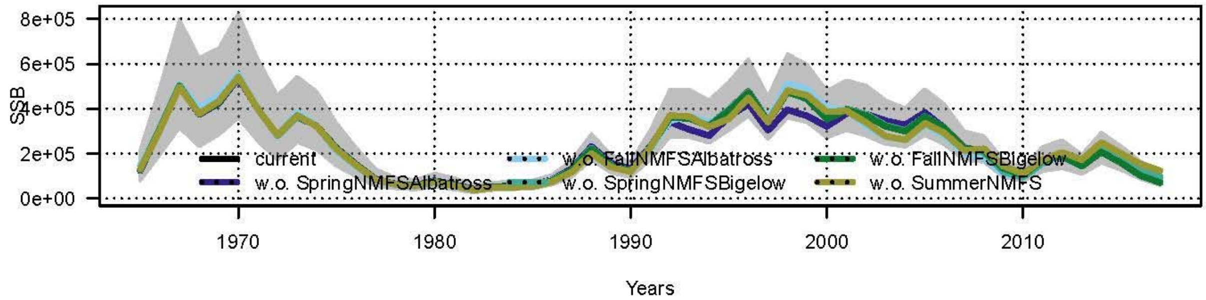

$\overline{F}_{4-6}$
0.0
0.2
0.4
0.6
0.8
1970
1980
1990
2000
2010
Years

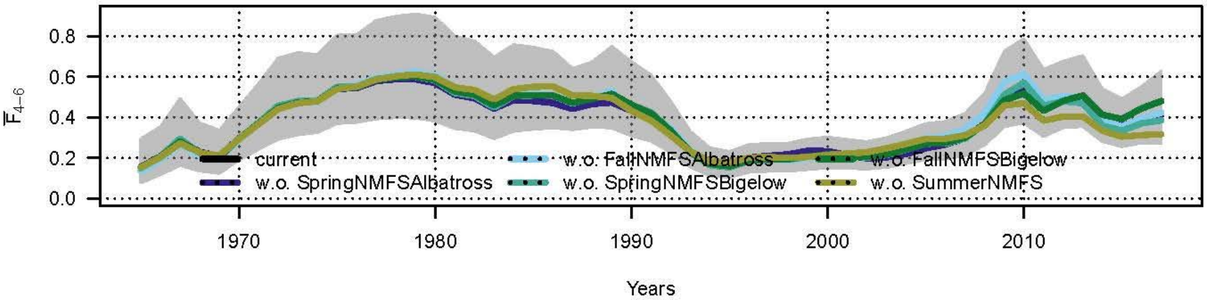

Recruits (age 1)
3.0e+07
2.5e+07
2.0e+07
1.5e+07
1.0e+07
5.0e+06
0.0e+00
1970
1980
1990
2000
2010
Years

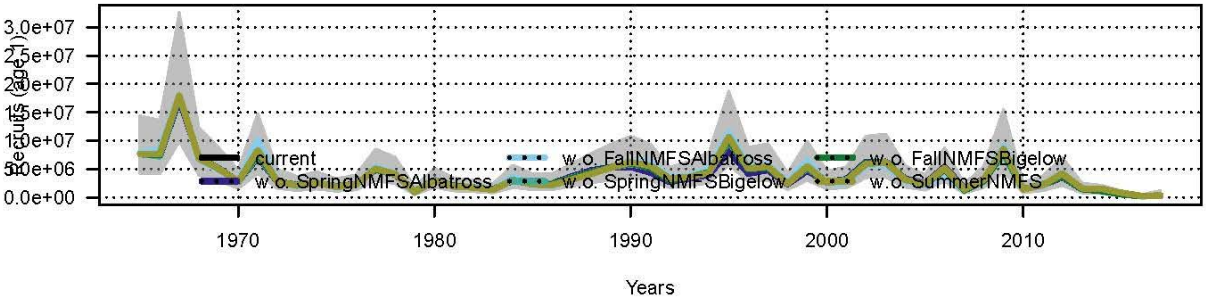

SSB
8e+05
6e+05
4e+05
2e+05
0e+00
1970
1980
1990
2000
2010
Years

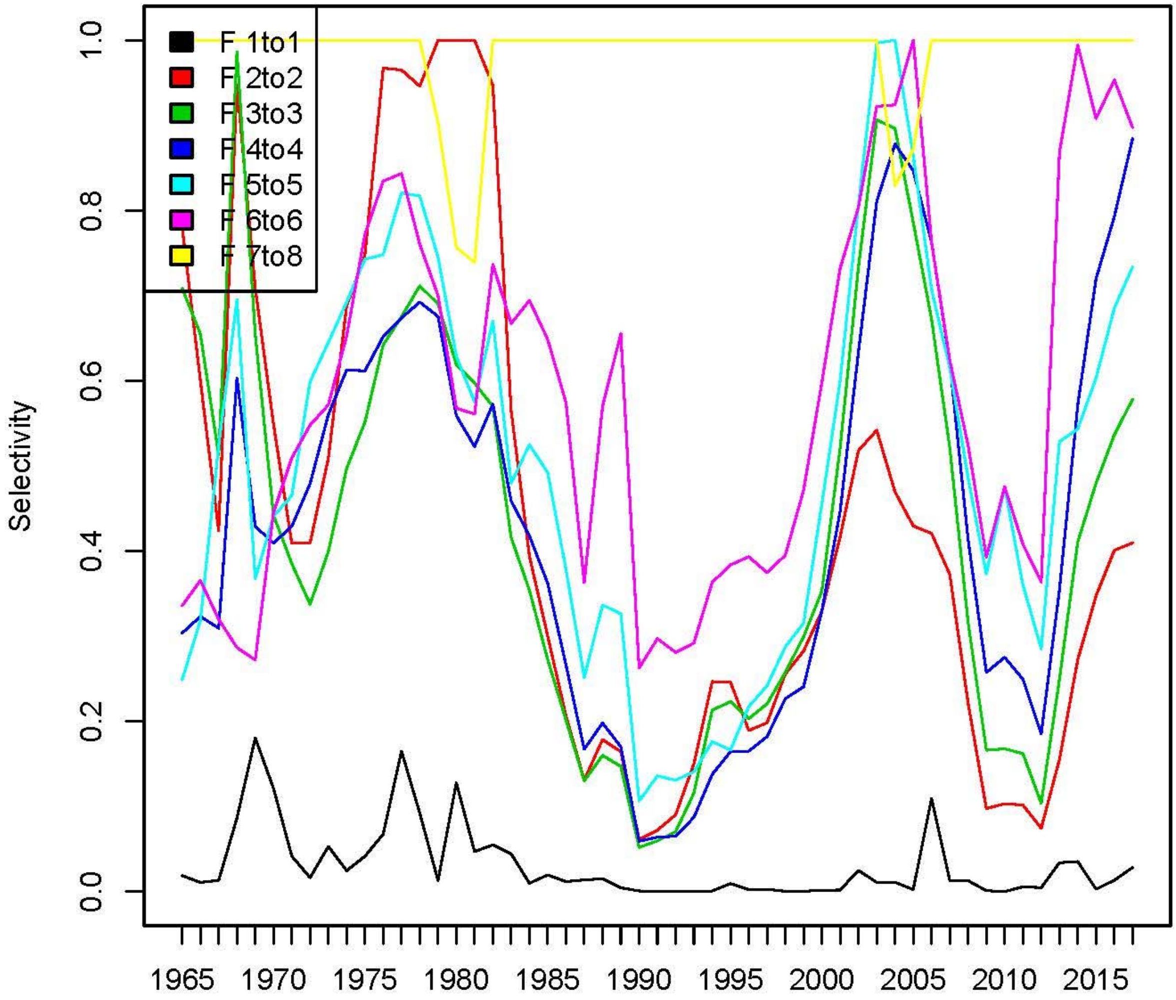

Residual catch
SummerNMFS
SpringNMFSAlbatross
SpringNMFSBigelow
FallNMFSAlbatross
FallNMFSBigelow
Age
0
2
4
6
8
1970
1980
1990
2000
2010
2020
Year
−6
−4
−2
0
2
4

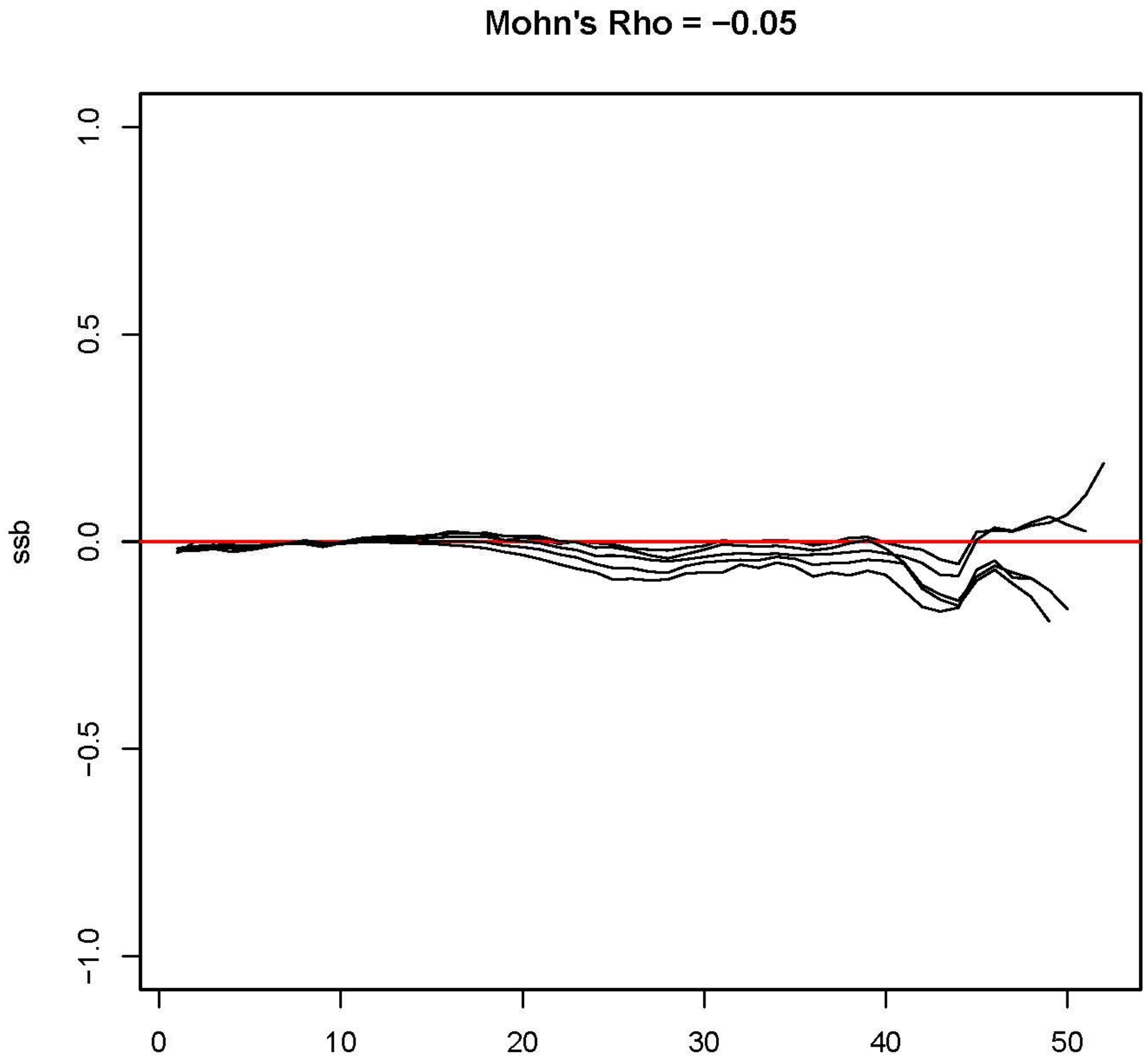

Joint sample residuals log(N)
Joint sample residuals log(F)
Age
0
2
4
6
8
Year
1970
1980
1990
2000
2010
−4
−3
−2
−1
0
1
2
3
4


SSB
8e+05
6e+05
4e+05
2e+05
0e+00
current
w.o. SpringNMFSAlbatross
w.o. FallNMFSAlbatross
w.o. SpringNMFSBigelow
w.o. FallNMFSBigelow
w.o. SummerNMFS
1970
1980
1990
2000
2010
Years


F̄4–6
0.8
0.6
0.4
0.2
0.0
current
w.o. SpringNMFSAlbatross
w.o. FallNMFSAlbatross
w.o. SpringNMFSBigelow
w.o. FallNMFSBigelow
w.o. SummerNMFS
1970
1980
1990
2000
2010
Years


Recruits (age 1)
3.0e+07
2.5e+07
2.0e+07
1.5e+07
1.0e+07
5.0e+06
0.0e+00
current
w.o. SpringNMFSAlbatross
w.o. FallNMFSAlbatross
w.o. SpringNMFSBigelow
w.o. FallNMFSBigelow
w.o. SummerNMFS
1970
1980
1990
2000
2010
Years


■ F 1to1
■ F 2to2
■ F 3to3
■ F 4to4
■ F 5to5
■ F 6to6
■ F 7to8
Selectivity
0.0
0.2
0.4
0.6
0.8
1.0
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015


Mohn's Rho = −0.05
ssb
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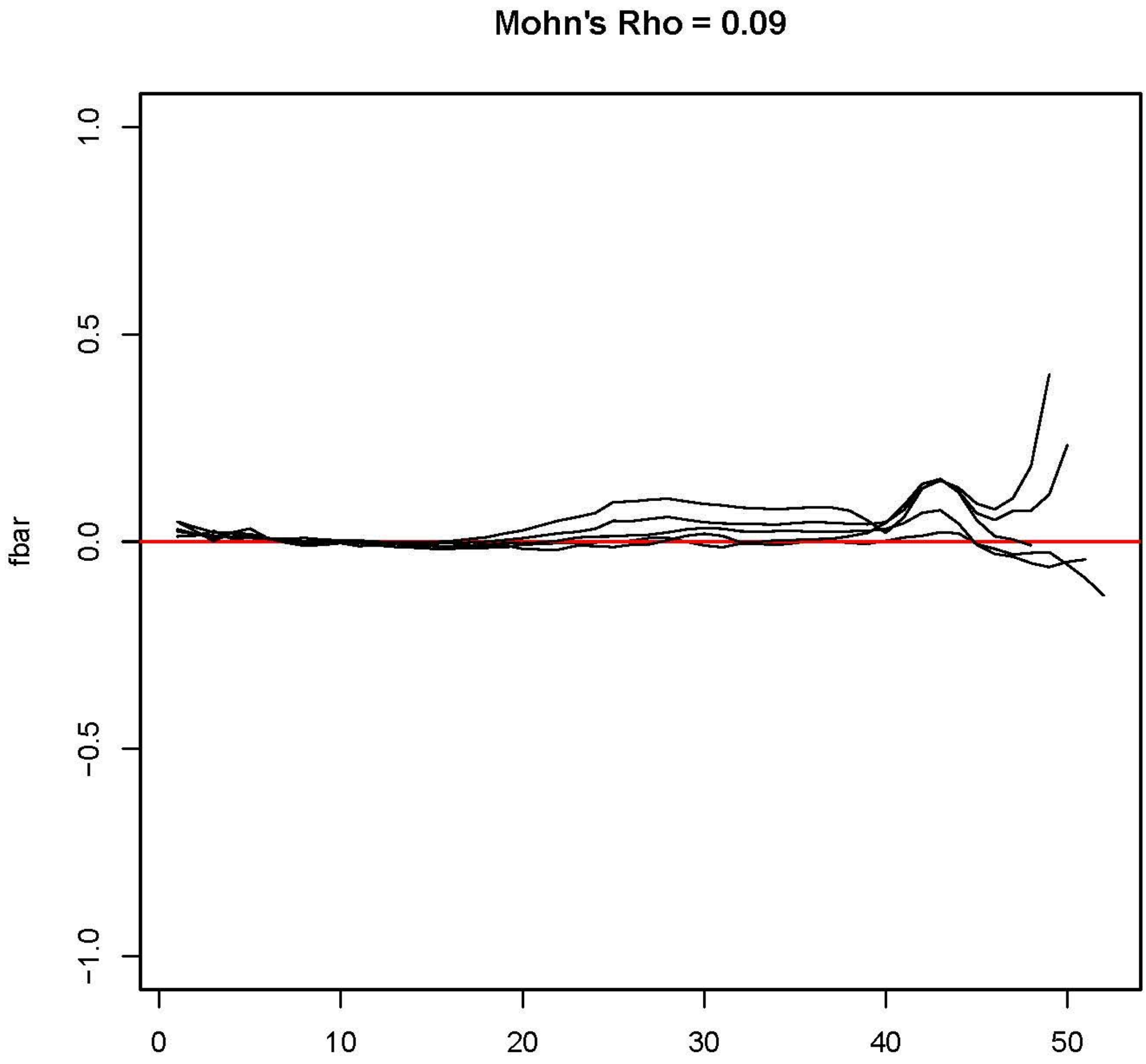
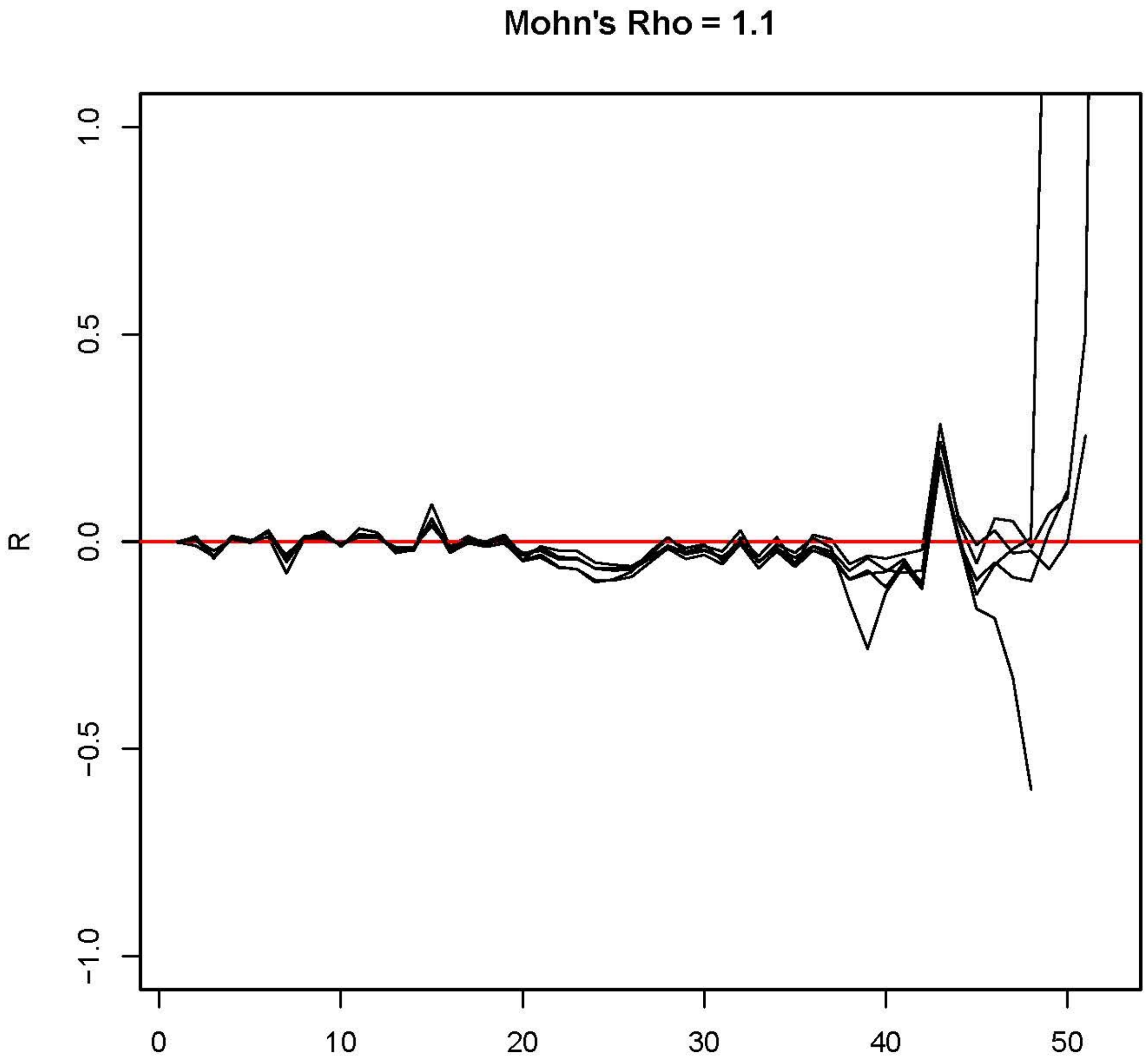
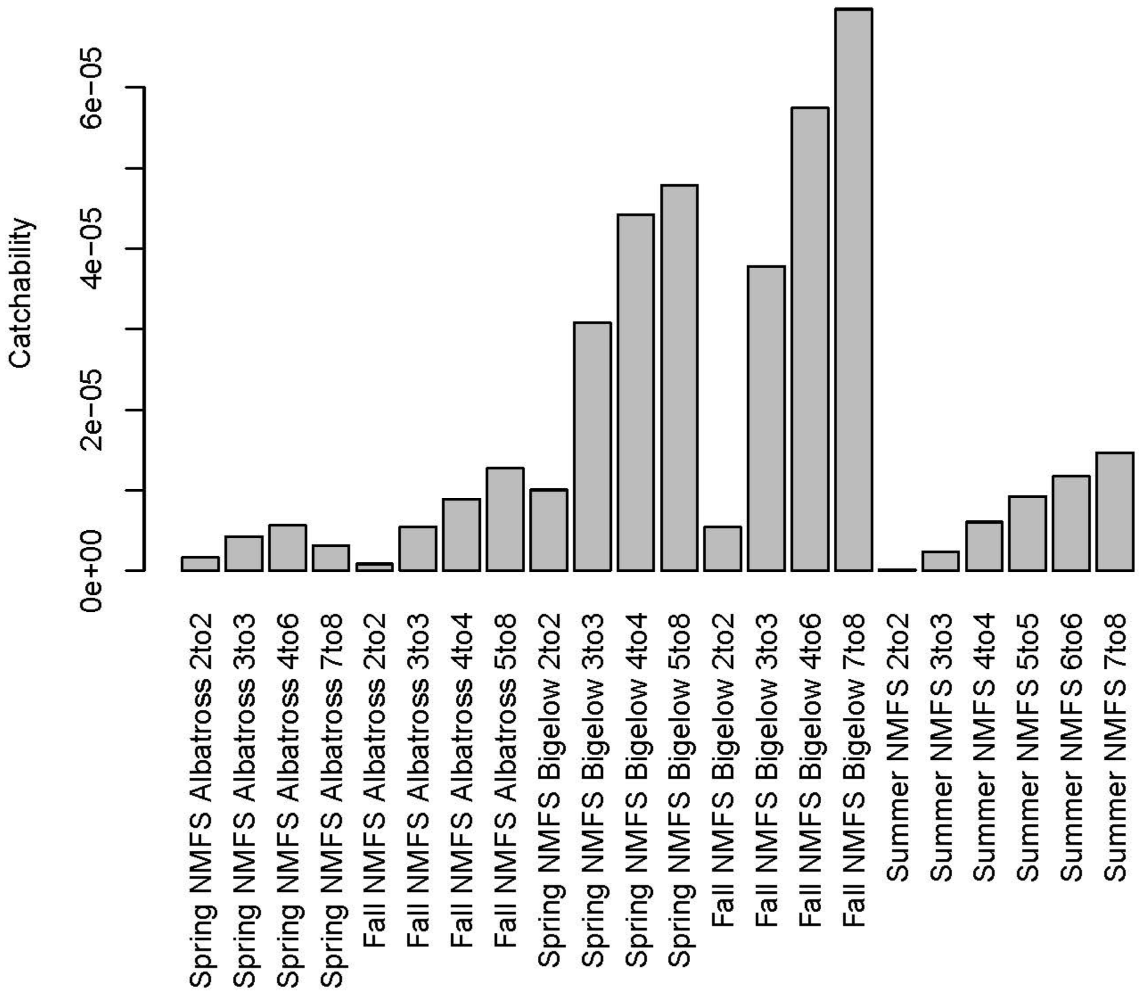
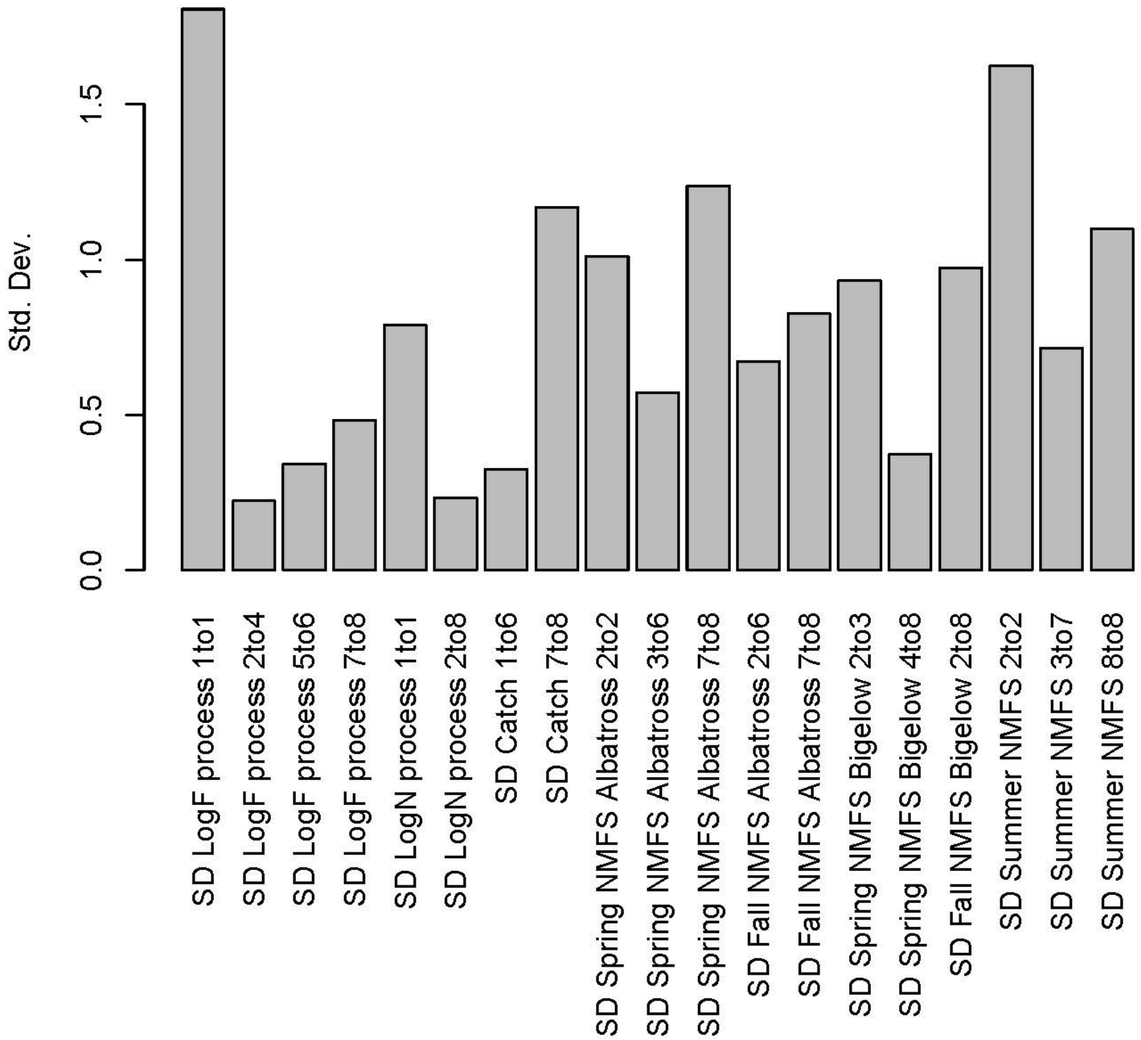
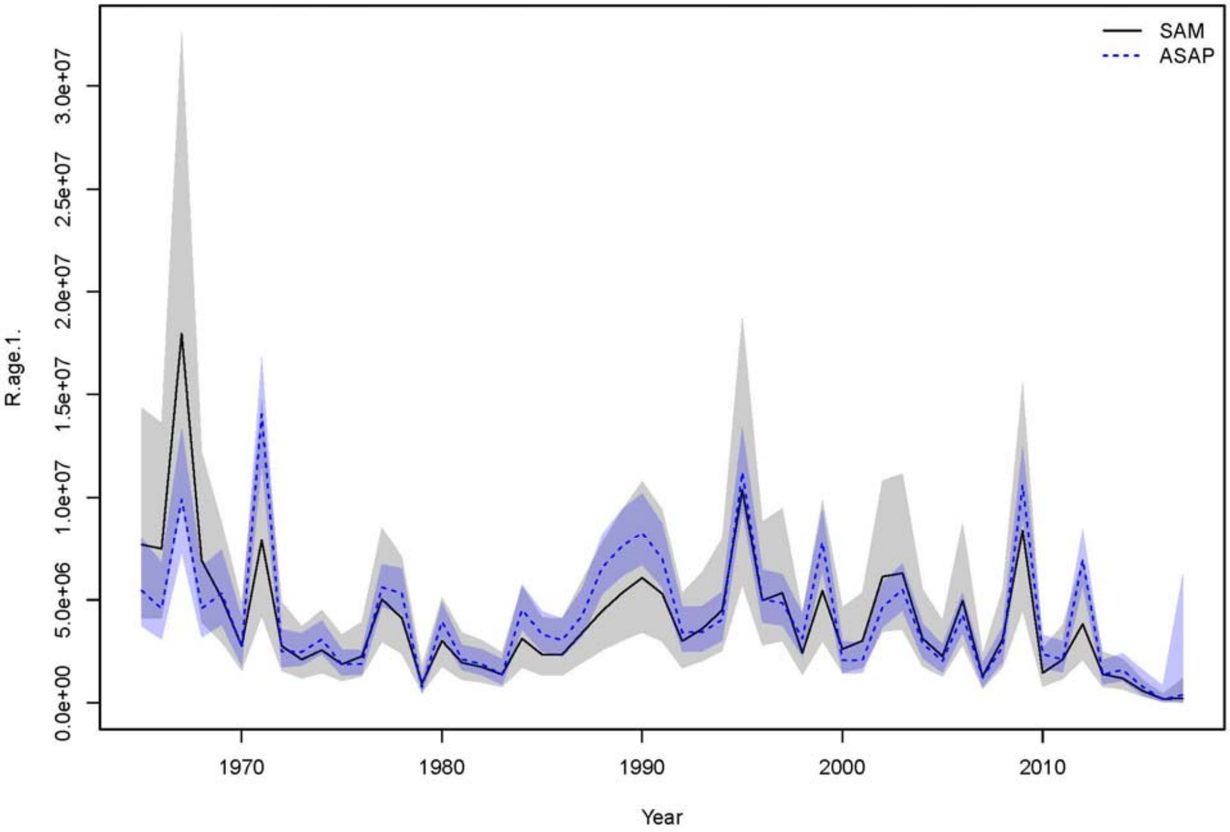
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50


Mohn's Rho = 0.09
fbar
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50


Mohn's Rho = 1.1
R
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50


Catchability
0e+00
2e-05
4e-05
6e-05
Spring NMFS Albatross 2to2
Spring NMFS Albatross 3to3
Spring NMFS Albatross 4to6
Spring NMFS Albatross 7to8
Fall NMFS Albatross 2to2
Fall NMFS Albatross 3to3
Fall NMFS Albatross 4to4
Fall NMFS Albatross 5to8
Spring NMFS Bigelow 2to2
Spring NMFS Bigelow 3to3
Spring NMFS Bigelow 4to4
Spring NMFS Bigelow 5to8
Fall NMFS Bigelow 2to2
Fall NMFS Bigelow 3to3
Fall NMFS Bigelow 4to6
Fall NMFS Bigelow 7to8
Summer NMFS 2to2
Summer NMFS 3to3
Summer NMFS 4to4
Summer NMFS 5to5
Summer NMFS 6to6
Summer NMFS 7to8


Std. Dev.
0.0
0.5
1.0
1.5
SD LogF process 1to1
SD LogF process 2to4
SD LogF process 5to6
SD LogF process 7to8
SD LogN process 1to1
SD LogN process 2to8
SD Catch 1to6
SD Catch 7to8
SD Spring NMFS Albatross 2to2
SD Spring NMFS Albatross 3to6
SD Spring NMFS Albatross 7to8
SD Fall NMFS Albatross 2to6
SD Fall NMFS Albatross 7to8
SD Spring NMFS Bigelow 2to3
SD Spring NMFS Bigelow 4to8
SD Fall NMFS Bigelow 2to8
SD Summer NMFS 2to2
SD Summer NMFS 3to7
SD Summer NMFS 8to8


SAM
ASAP
R.age.1.
0.0e+00
5.0e+06
1.0e+07
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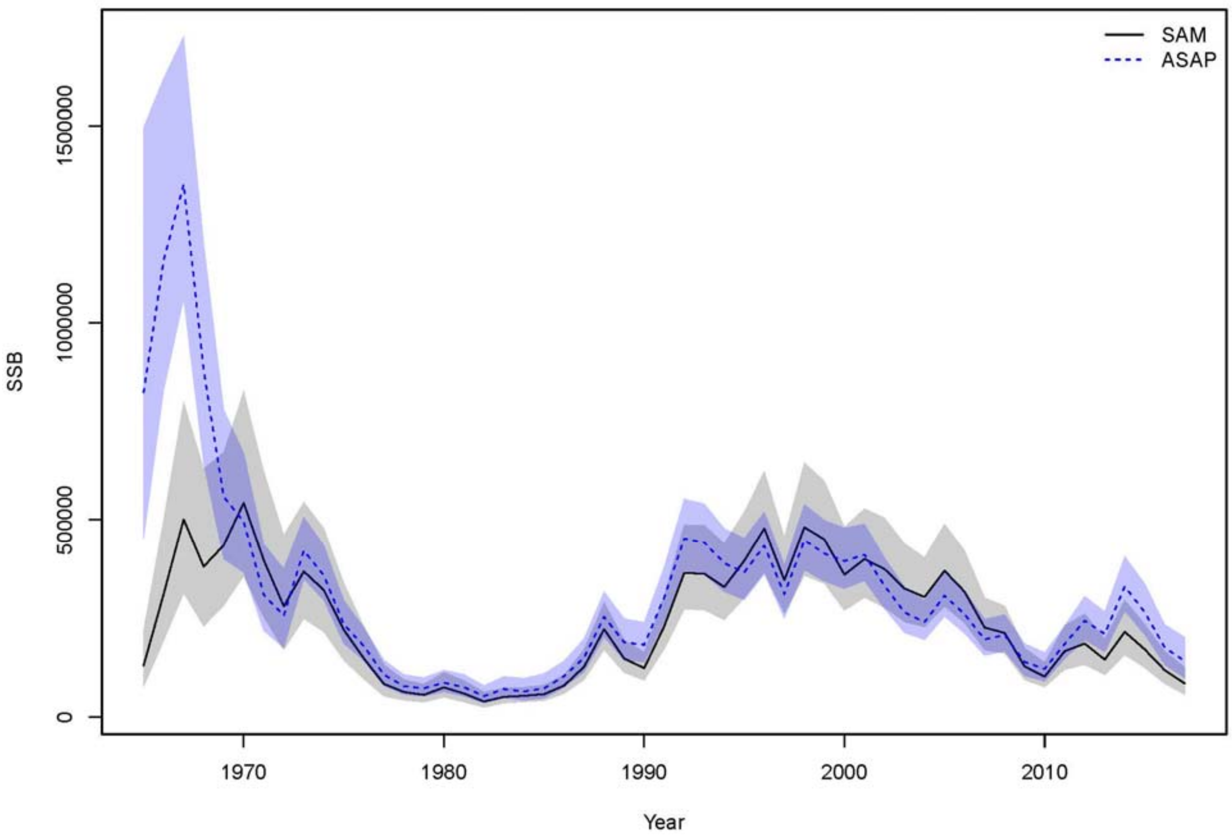
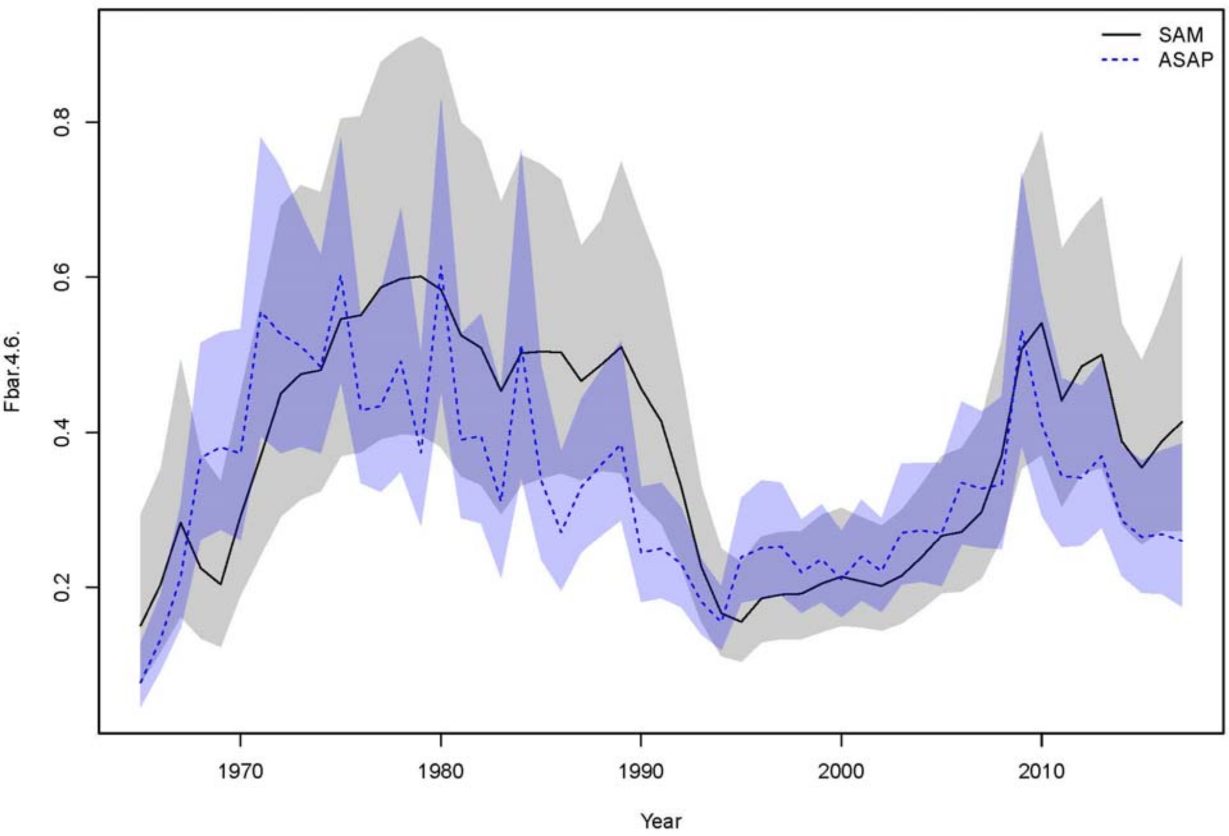
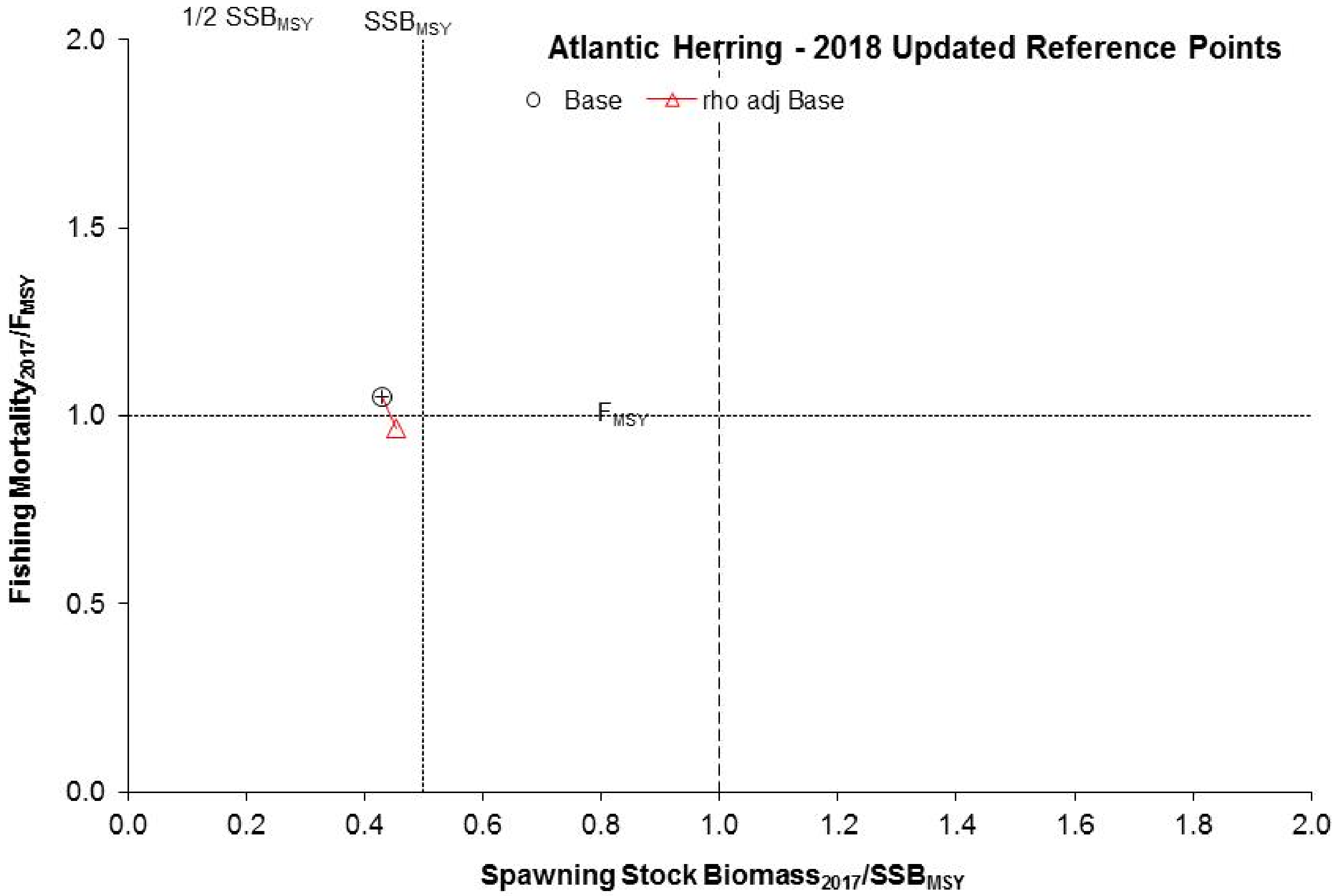
2.0e+07
2.5e+07
3.0e+07
1970
1980
1990
2000
2010
Year


SAM
ASAP
SSB
0
500000
1000000
1500000
1970
1980
1990
2000
2010
Year


SAM
ASAP
Fbar.4.6.
0.2
0.4
0.6
0.8
1970
1980
1990
2000
2010
Year


Atlantic Herring - 2018 Updated Reference Points
○ Base
△ rho adj Base
1/2 SSB$_{MSY}$
SSB$_{MSY}$
F$_{MSY}$
Fishing Mortality$_{2017}$/F$_{MSY}$
Spawning Stock Biomass$_{2017}$/SSB$_{MSY}$
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Appendix B3

Consideration of a model ensemble – model averaging ASAP and SAM (in prep)

Appendix B4

Two area Stock Synthesis application (In prep).

Appendix B5

Working Paper: Predation Pressure Index to Inform Natural Mortality

Jonathan J. Deroba

Objective

Develop an index of predation pressure (Richards and Jacobson2016) to inform time-varying natural mortality (M) in Atlantic herring.

Methods

Food habits and data to estimate indices of herring predator biomass were collected on NMFS Northeast Fisheries Science Center spring and fall bottom trawl surveys. Details about the methods for sampling food habits data, including the stomach contents data used here, can be found in Link and Almeida (2000) and Smith and Link (2010). Details about bottom trawl survey design and sampling can be found in Grosslein (1969), Azarovitz (1981), and Miller et al. (2010).

A predation pressure index (PPI) was estimated for predators that had at least 10 stomachs containing herring and positive occurrences of herring in at least 0.1% of stomachs, combined among all years and seasons. These criteria were met by 15 predators (Table 1), and the list is similar to that used to estimate annual consumption in recent herring assessments (NEFSC 2012).

A percent frequency of occurrence of herring in predator stomachs was estimated as the percentage of stomachs containing herring (P), combined among years and seasons:

$$P_p = \frac{\sum_y S_{y,p}}{\sum_y T_{y,p}} \times 100;$$

where p is predator, y is year, S is the number of stomachs containing herring (i.e., positive occurrences), and T is the total number of stomachs examined.

Annual indices of predator biomass (B; stratified mean kg per tow) were estimated for the spring and fall bottom trawl surveys for each of the predators (except striped bass and sea raven, see below). Indices for each predator were estimated as in their respective stock assessments (index values were downloaded from the PopDy Branch "ADIOS" system on June 8, 2017). For predators that have indices estimated separately by region or sex (Table 1), values were summed to obtain season specific (spring and fall) annual indices. Sea raven were excluded from the analysis because this species has no stock assessment and indices were unavailable, but they likely account for a relatively small amount of herring predation (NEFSC 2012), and so results and conclusions are likely robust to this omission. Time series of indices of biomass and percent frequency of occurrence began in 1968 in the spring and 1963 in the fall.

The striped bass stock assessment does not use the spring and fall bottom trawl survey data for indices of biomass because the gear does not provide a suitable index. In order to accommodate striped bass in the calculation of PPI, estimates of total striped bass biomass from the stock assessment were rescaled to equal the average of all the other predator biomass indices among seasons and years, and this annual quantity was used for both seasons in the calculation of PPI:

$$B_{y,bass} = \frac{E_y}{\bar{B}};$$

where $B_{y,bass}$ is the value treated as the year specific index of biomass for striped bass in both seasons, $E$is the estimate of total striped bass biomass from the stock assessment, and $\bar{B}$ is the mean index of predator biomass among all other predators, years, and seasons. This rescaling of the striped bass total biomass estimates was done so that the scale of the index values used for striped bass in the calculation of PPI were similar to other predators. The PPI was calculated with and without striped bass included, and results were presented separately. The striped bass stock assessment begins in 1982, and so PPI calculations that included striped bass also began in 1982.

Season and year specific PPI was calculated as the weighted average of the predator indices of biomass (B):

$$PPI_{y,s} = \sum_p B_{y,s,p} \times P_p;$$

where s denotes season (spring or fall).

Time-varying M was calculated by adjusting a base M by annual deviations in PPI from the mean PPI:

$$M_{y,s} = \frac{M_b \times PPI_{y,s}}{\overline{PPI_s}};$$

where M_b was a baseline level of natural mortality, which equaled 0.35 for demonstration purposes, but was derived from Hoenig (1983) and has been used in previous herring stock assessments (NEFSC 2012).

Results

Temporal trends in PPI were similar between seasons, with and without striped bass. Without striped bass, PPI declined from the beginning of each time series, varied without trend below the time series means after ~1990, and increased since ~2010 to near the time series means in the most recent year (Figure 1). With striped bass, PPI has generally varied without trend near the time series means (Figure 1). Results for M were similar to PPI. Without striped bass, M declined from the beginning of each time series, varied without trend below the below the baseline rate after ~1990, and increased since ~2010 to near the baseline level (Figure 2). With striped bass, M generally varied without trend near the baseline level (Figure 2).

Discussion

The 2012 herring stock assessment increased M from 0.35 (averaged among ages) to 0.50 beginning in 1996 (NEFSC 2012). This increase in M eliminated a retrospective pattern and produced generally consistent amounts of consumption between that implied by the input M and that estimated from stomach contents data. These two justifications for increased M no longer held in the 2015 updated herring stock assessment, with a worsened retrospective pattern and consumption of herring implied by the input M being higher than that estimated from stomach contents data (Deroba 2015). The trends in PPI, and subsequent deviations from M_b, were also inconsistent with the increased M rates used in the 2012 and 2015 herring stock assessments.

The PPI and consumption estimates both use some of the same stomach contents data, but suggest different conclusions about variation in M. This inconsistency could be related to caveats in the calculation of PPI, consumption, the herring stock assessment, or a combination. The estimates of consumption, for example, have been criticized as likely to be biased in scale and trend due to reliance on estimates of predatory biomass from stock assessments and other sources with different underlying structural assumptions and uncertainties (Brooks and Deroba 2015). The strength of evidence for an increase in M provided by the estimates of consumption also depends on aspects of the herring assessment itself. Assumptions and input data to the herring assessment determine the scale and trend of the resulting assessment estimates, and estimates of consumption from the stomach contents data are compared to consumption implied by the input M and this requires use of herring assessment estimates. The assumptions and input data for the herring assessment, however, are also subject to uncertainties.

The PPI and consumption calculations also ignore spatial and seasonal variation (other than spring and fall) in the overlap and efficiency of predators and Atlantic herring. The probability of a predator stomach containing herring and the amount of herring in a stomach vary seasonally and spatially (Deroba 2018). Ignoring such variation may cause bias and a false sense of precision in the PPI and consumption estimates.

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Smith, B.E., Link, J.S. 2010. The trophic dynamics of 50 finfish and 2 squid species on the Northeast US Continental Shelf. NOAA Tech. Mem., NMFS-NE-216.

Figure 1.—Predation pressure index (PPI) for Atlantic herring calculated in the spring and fall, without (top panel) and with (bottom panel) striped bass. Red horizontal lines are time series means in the spring and fall.

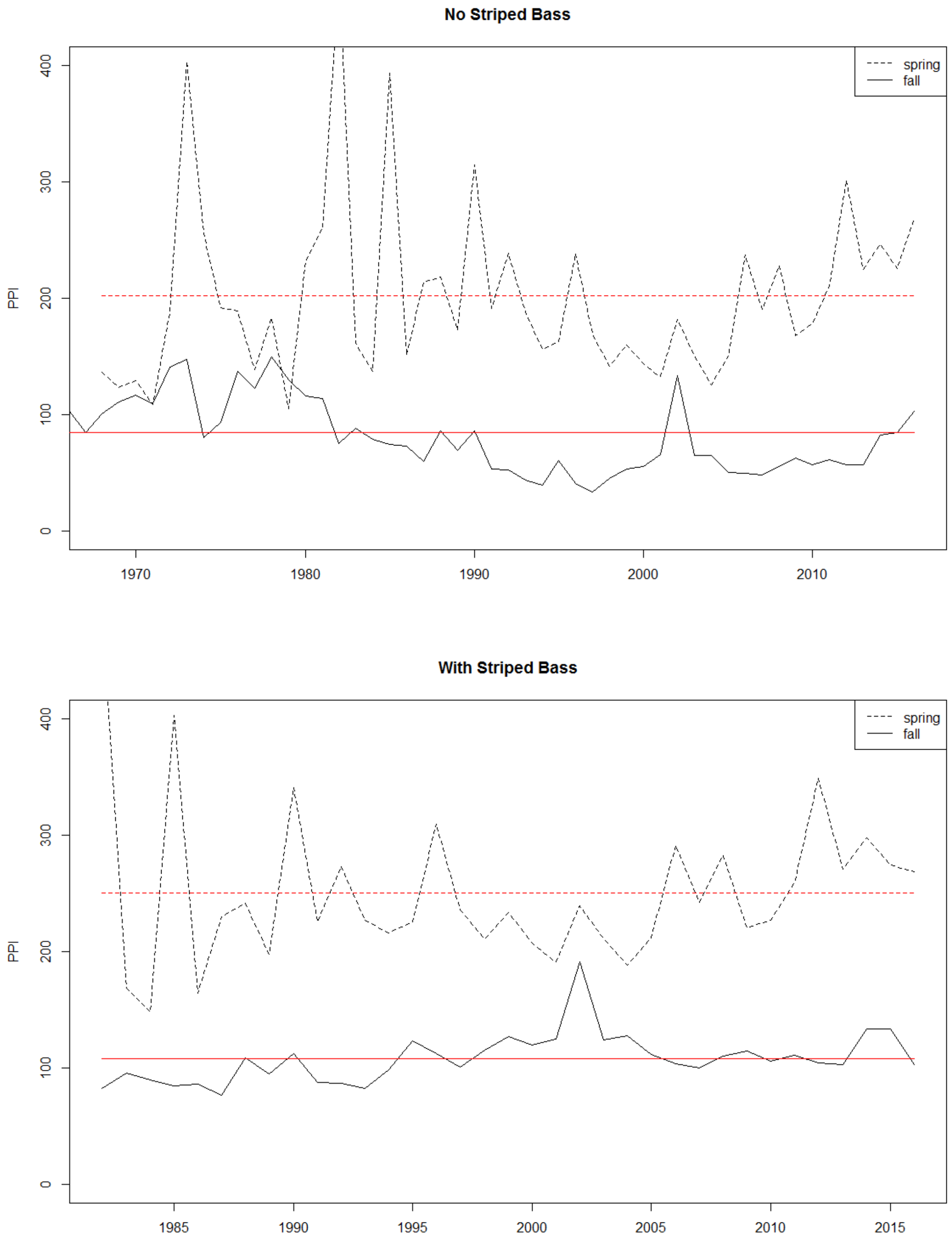

Figure 2.—Natural Mortality (M) for Atlantic herring calculated in the spring and fall, without (top panel) and with (bottom panel) striped bass. Red horizontal lines indicate a baseline M level of 0.35.

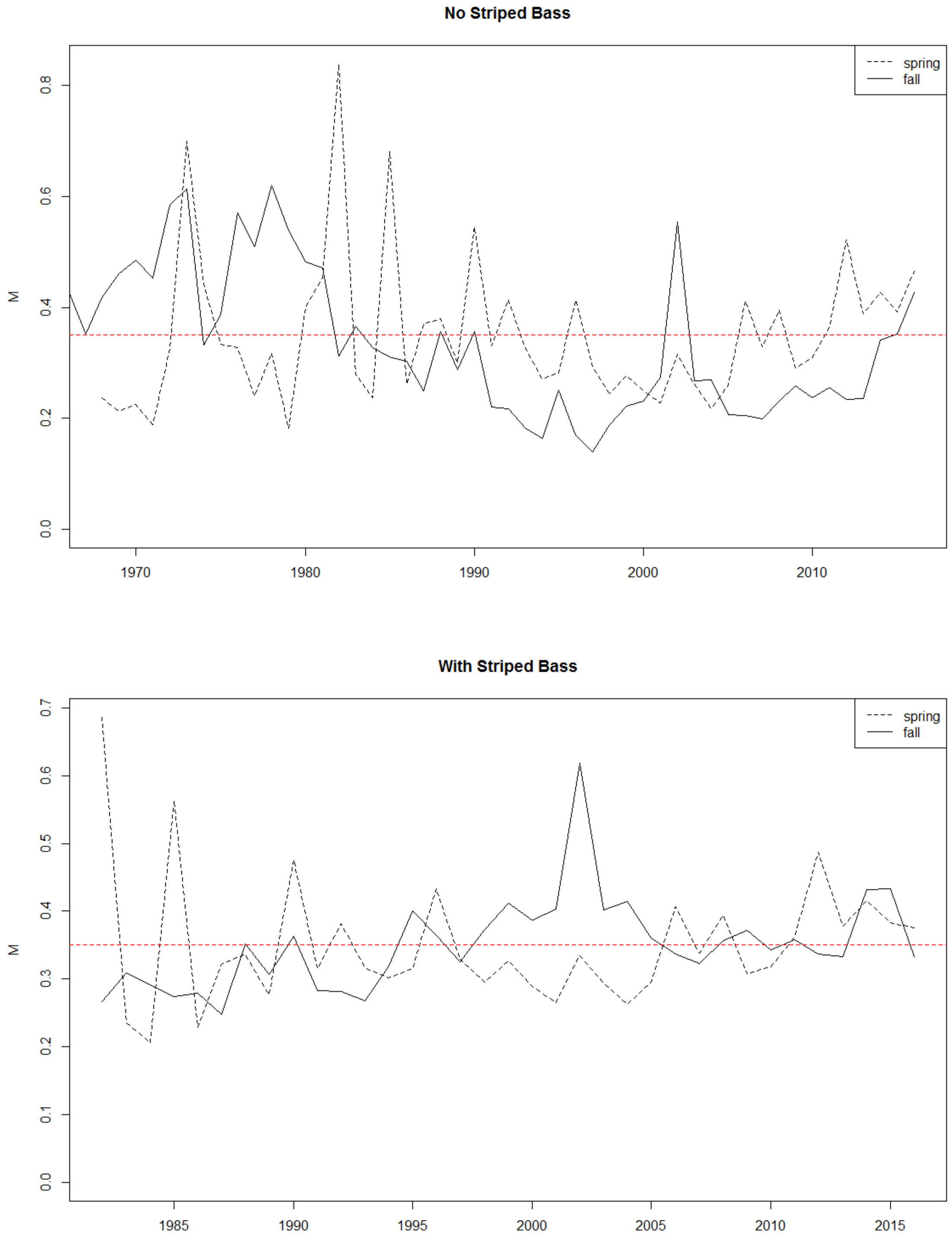

Table 1.—Herring predators that had at least 10 stomachs containing herring and positive occurrences of herring in at least 0.1% of stomachs, combined among all years and seasons, and used to estimate a predation pressure index.

PREDATOR	**Region (R) or Sex (S) distinctions**
ATLANTIC_COD	R – Georges Bank, Gulf of Maine
ATLANTIC_HALIBUT	NA
BLUEFISH	NA
GOOSEFISH	R – North, South
HADDOCK	R – Georges Bank, Gulf of Maine
POLLOCK	NA
RED_HAKE	R – North, South
SEA_RAVEN	NA
SILVER_HAKE	R – North, South
SPINY_DOGFISH	S – Male, Female, Unidentified
STRIPED_BASS	NA
SUMMER_FLOUNDER	NA
THORNY_SKATE	NA
WHITE_HAKE	NA
WINTER_SKATE	NA

Appendix B6

The NEFSC Study Fleet Program's Fisheries Logbook Data and Recording Software and its use the Atlantic Herring Fishery

Submitted by

Christopher L Sarro – NEFSC Cooperative Research Program

The Northeast Fisheries Science Centers (NEFSC) Cooperative Research Branch's Study Fleet program began development in late 2000. The pilot program had two main goals: 1) assemble a 'study fleet' of commercial New England groundfish vessels capable of providing high resolution (temporal and spatial) self-reported data on catch, effort and environmental conditions while conducting normal fishing operations; and 2) developing and implementing electronic reporting hardware and software for the collection, recording and transferring of more accurate and timely fishery-based data (Palmer et al 2007).

The program was developed to provide stock assessment scientists with fisheries dependent data that could provide more precise estimates of fishing effort and spatially-specific catch and discard rates. The collaborative nature of the program could also provide a means of communication between industry and science for better understanding of factors driving fishing effort and catch, as well as serve as platform for future collaborative projects (Palmer et al 2007).

Phase I began in late 2002, with a fleet of 15 paid participants, to develop an electronic logbook (ELB) and test supporting hardware. Phase II began in September 2004, with 30 participating vessels, to continue developing the ELB and explore satellite communication (Palmer et al 2007). Study Fleet is currently in Phase III, with a fully functioning ELB for data collection and transfer, auditing and utilization of data and enhanced biological sampling. Currently, there are over 40 contracted vessels in Study Fleet with homeports ranging from North Carolina to New Hampshire. Participating vessels range from New Hampshire to North Carolina with concentrations in Cape May, New Jersey and Point Judith, Rhode Island. The majority of vessels fish bottom trawl gear, though there are also gillnet, longline and scallop vessels participating.

The ELB developed for use in the Study Fleet program was the Fisheries Logbook and Data Recording Software (FLDRS). This is free software developed by the NEFSC, which is capable of reporting on the haul-by-haul and subtrip levels. FLDRS is currently on its fourth version with version five in development. On all vessels, FLDRS connects to a GPS unit or satellite compass and polls the unit every 20 seconds for accurate location information. FLDRS can be integrated with the depth sounder for depth information and/or a vessel monitoring system for rapid data transmission via satellite. The newest version of FLDRS is also capable of sending trip and GPS data via email if the software can access a Wi-Fi connection.

Gear-mounted temperature/depth probes are also deployed on vessels. The temperature/depth probes collect temperature and depth data every 90 seconds. Earlier models would poll continually and needed to be downloaded every 30-90 days. Current models are depth triggered and the data is uploaded after each tow to an onboard computer via a Bluetooth connection. Future improvements to FLDRS will allow for email transmission of temperature/depth files as well.

FLDRS can collect data on both the trip and haul levels. On the trip level, FLDRS collects program code, vessel and operator information, sail and landing date and port, number of efforts, aggregated fishing time, catch, apportionment and dealer information. On the haul level, FLDRS also collects fishing gear, tow specific location, duration, depth, statistical area and catch information.

FLDRS is also capable of collecting 'Dynamic Data'. These are additional data elements that are specific to certain gear types or program code. The Herring Program Code was developed with Massachusetts Division of Marine Fisheries (MADMF) to assist with their River Herring Bycatch Avoidance Program. Under the Herring Program Code, captains record which herring management sub-area they intend on fishing, the percent river herring catch and estimated river herring weight if a fisheries observer is present.

During installation, FLDRS is customized to each vessel and its fishing activities. All the various gears that a vessel uses, with the necessary gear characteristics (gear code, sweep length, mesh size and mesh type) are saved in FLDRS. Each gear is also associated with a customized species list of the most common kept and discarded species caught with that particular gear. All dealers that a vessel sells to are added to a dealer list. Finally, vessels' defaults are set up; these are the operator, gear, port, crew size and trip type that populate in the software automatically.

In July 2011, the Greater Atlantic Regional Office (formerly the Northeast Regional Office) approved the use of electronic Vessel Trip Reporting (eVTR) for a segment of the groundfish fleet and was expanded to other fisheries in 2013. FLDRS is now one of six approved eVTR platforms. During 2014-2015, the Cooperative Research Branch collaborated with the Pacific States Marine Fisheries Commission (PSFMC) to expand electronic reporting in the Northeast fisheries. This effort made funding available for up to 120 participating vessels to receive computers, installation, hardware and training in the use of FLDRS. A subset of these vessels also received temperature/depth probes. To date, 234 vessels have used FLDRS for haul-by-haul and subtrip reporting for research and eVTR purposes (Figure 1).

Use of FLDRS in the Atlantic herring Fishery:

Atlantic herring catches start in the Cooperative Research database in 2006. That year only a single vessel landed more than 2,200 lbs of Atlantic herring on an individual trip. The number of participant vessels participating in the Atlantic herring fishery ranged from one in 2006 to seven in 2013 with the vast majority of fishing effort coming from the small-mesh bottom trawl fishery off Rhode Island. Cooperative Research staff, through coordination with MADMF, made a concerted effort to install FLDRS on the mid-water and paired mid-water vessels through the collaboration with the PSMFC. This increase in vessels has greatly increased the amount of data collected from Atlantic herring fishery including fishing effort and the geographic footprint of the fishery. (Figures 2-4).

Midwater gear (both single and paired) is the most commonly occurring gear type in the time series. However, some small-mesh bottom trawl vessels out of Point Judith, RI will report using gear code 097OTM. The summer purse seine fishery in management sub-area 1A is not strongly represented with only one boat reporting using FLRDS in 2016 and two in 2017 (Figure 5). Vessels reporting haul-by-haul using FLDRS represented only 0.23 % of the total Atlantic herring landings in 2006. However, in 2016, vessels using FLDRS accounted for 41 % of the total Atlantic herring landings (Figure 6).

The participation of the commercial Atlantic herring fishery in haul-by-haul reporting has allowed for the collection of detailed information on effort and catch. Cooperative Research is attempting to integrate more of the onboard equipment such as net mensuration equipment for more accurate estimation of fishing time and catch per unit effort. This information combined with future improvements to FLDRS should be able address specific research and management questions.

Cooperative Research staff has fostered a close relationship with the commercial Atlantic herring industry, includes sailing on commercial vessels to examine trends in river herring bycatch and conducting a dedicated study to evaluate a predictive river herring distribution model in the small-mesh bottom trawl fishery. The direct lines of communication between Cooperative Research staff and members of the commercial Atlantic herring industry also provide insight into factors affecting fishing effort beyond availability. Variables such as fuel prices, market forces, seasonal closures, catch caps and availability of other species can influence catch beyond availability of the target species. Providing this information to stock assessment scientists and fisheries managers could prove valuable moving forward.

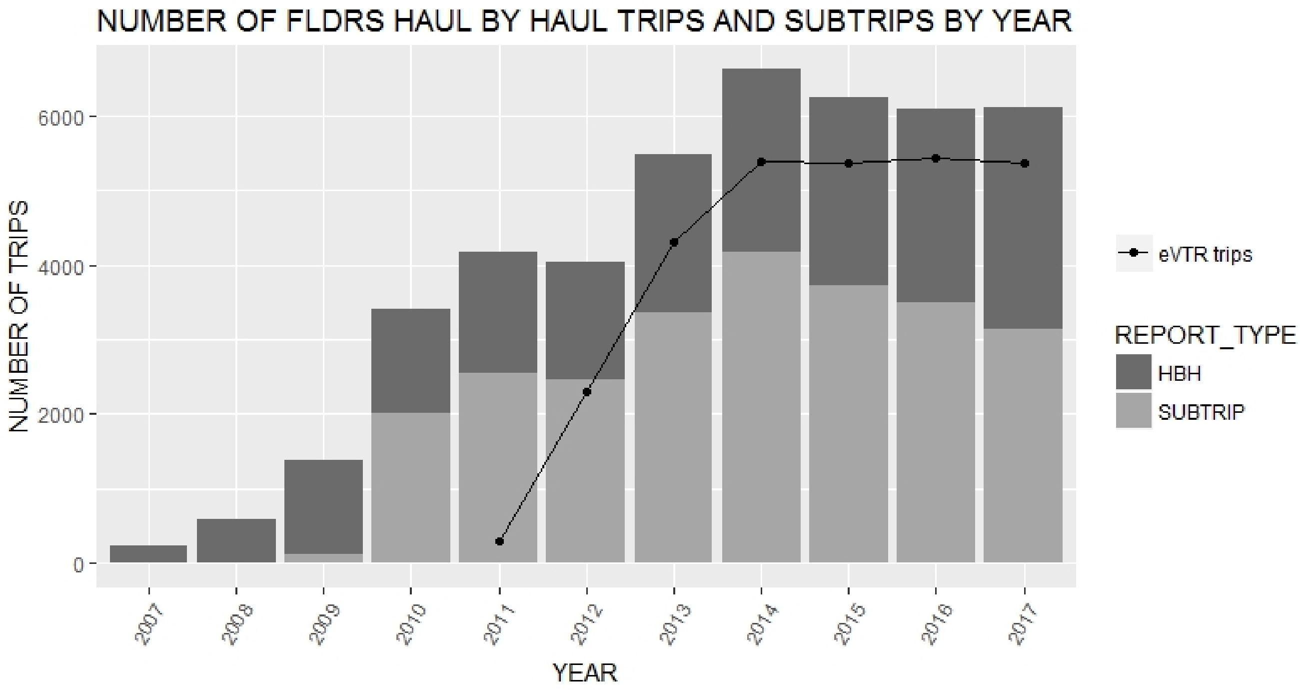

Figure 1: The number of trips (haul-by-haul and subtrip) and eVTRs per year from vessels using FLDRS.

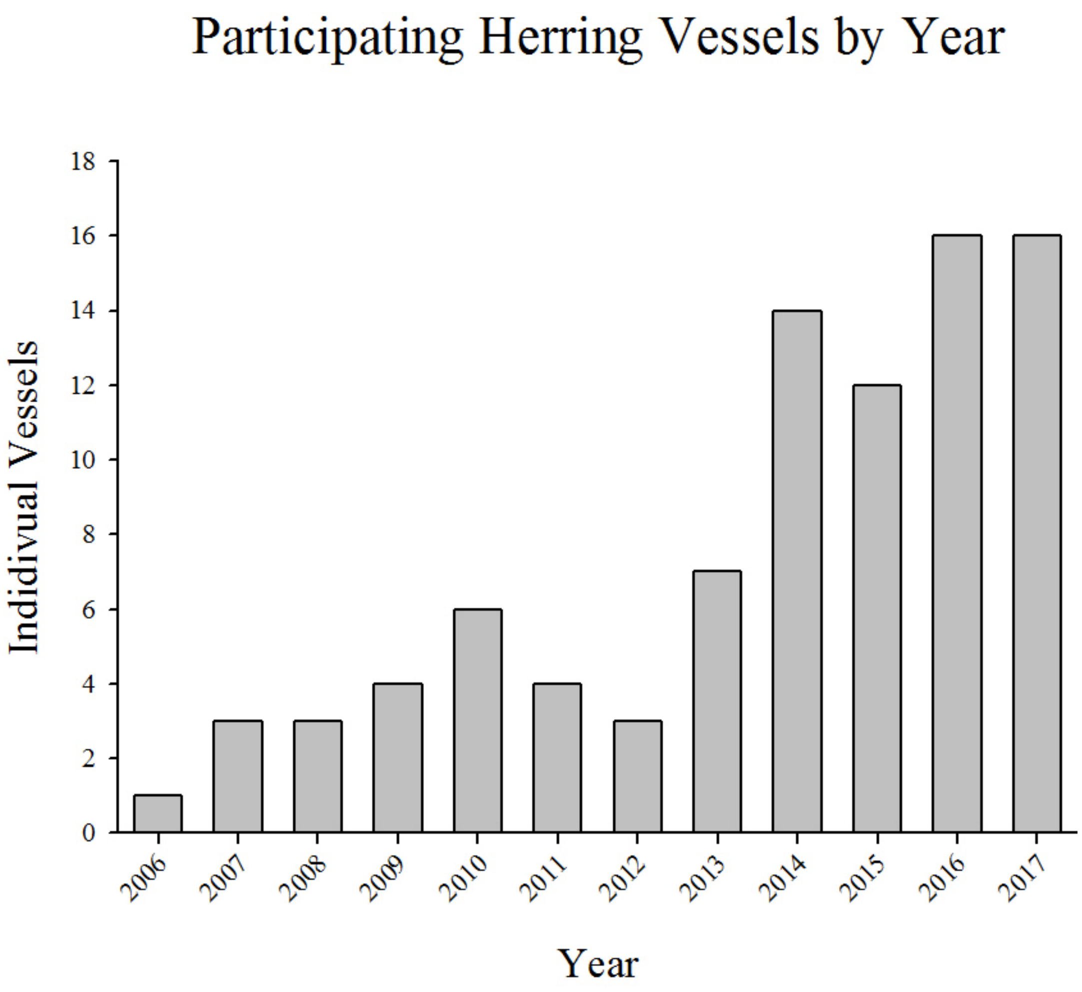

Figure 2: The number of individual vessel permit numbers that reported at least one haul-by-haul trip that landed > 2,200 lbs of Atlantic herring.

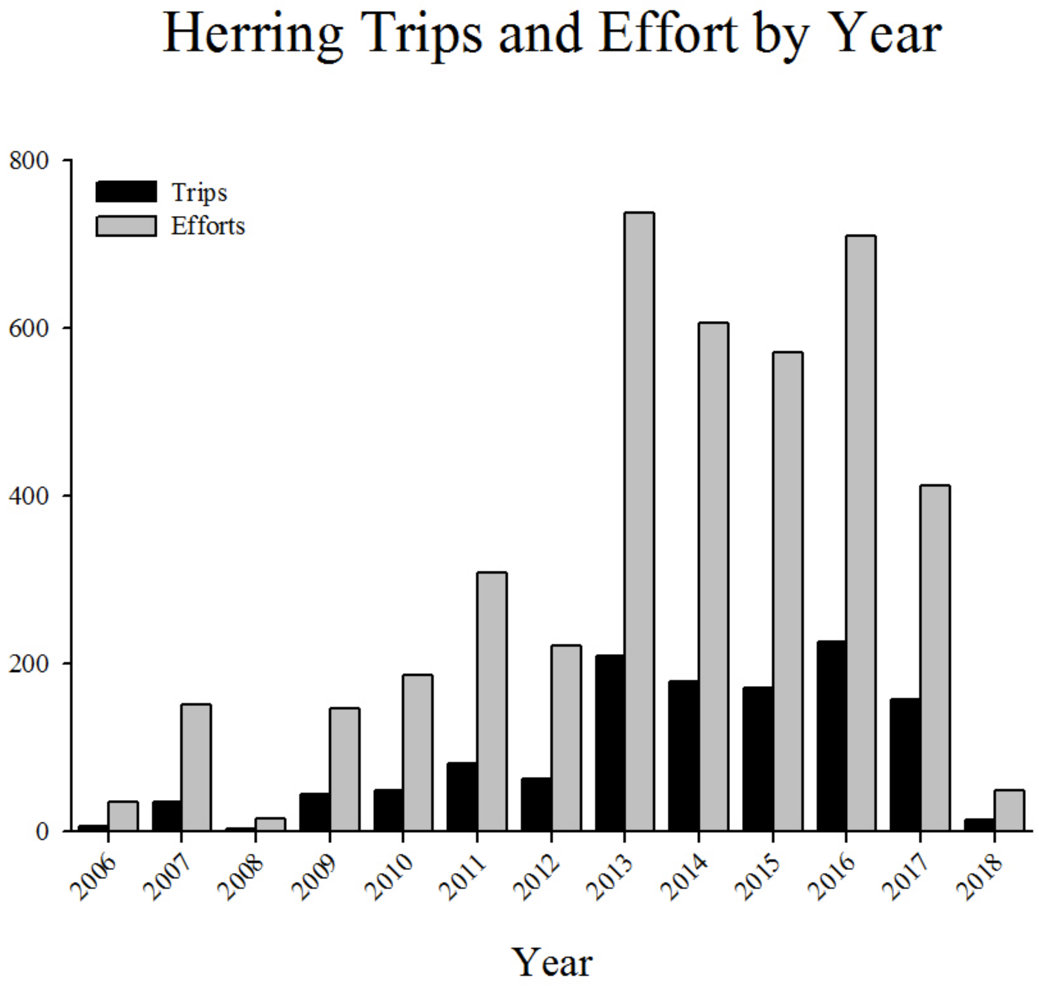

Figure 3: The number of trips and efforts that landed > 2,200 lbs of Atlantic herring. Trips and efforts from paired midwater trawlers were counted together as a single trip or effort.

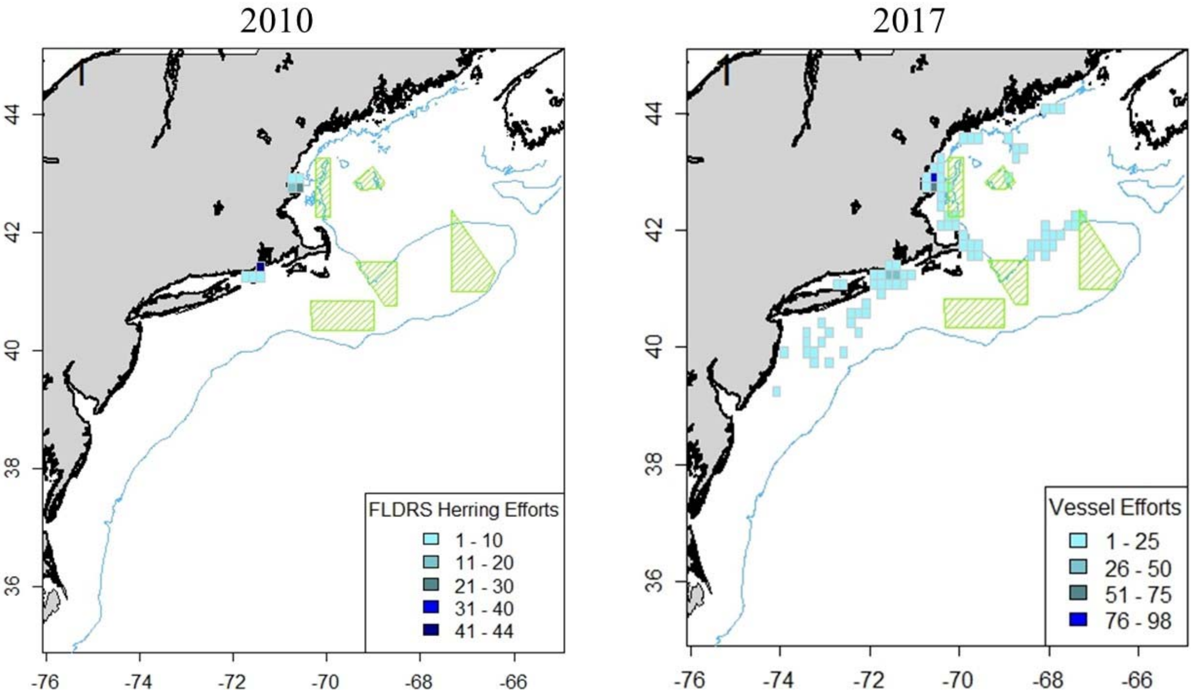

Figure 4: The number of efforts per 10 minute squares on trips landing more than 2,200 lbs of Atlantic herring from Cooperative Research Participants using FLDRS in 2010 and 2017.

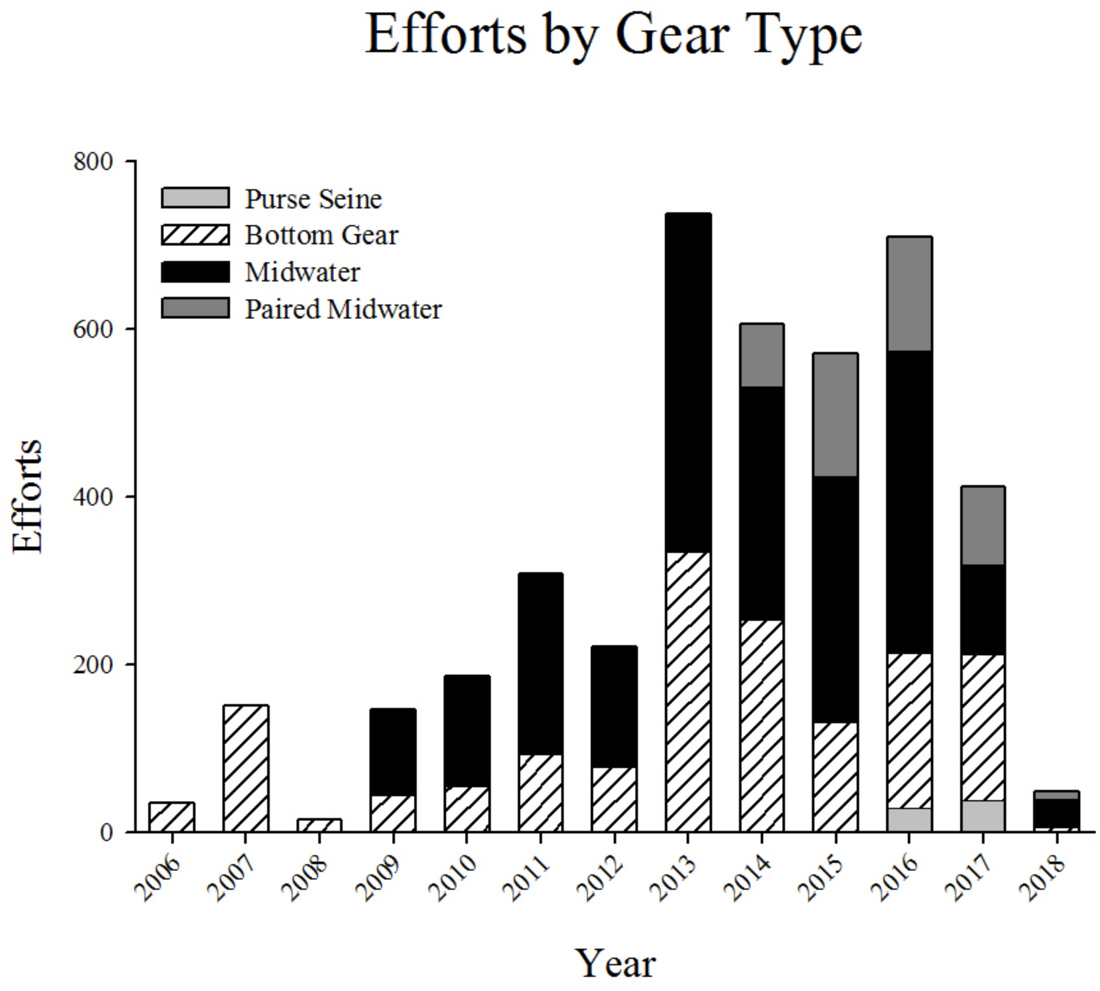

Figure 5: The number of efforts made using the various gear types by year. Bottom gear includes gear codes 090OTO, 092OTF and 092OTR.

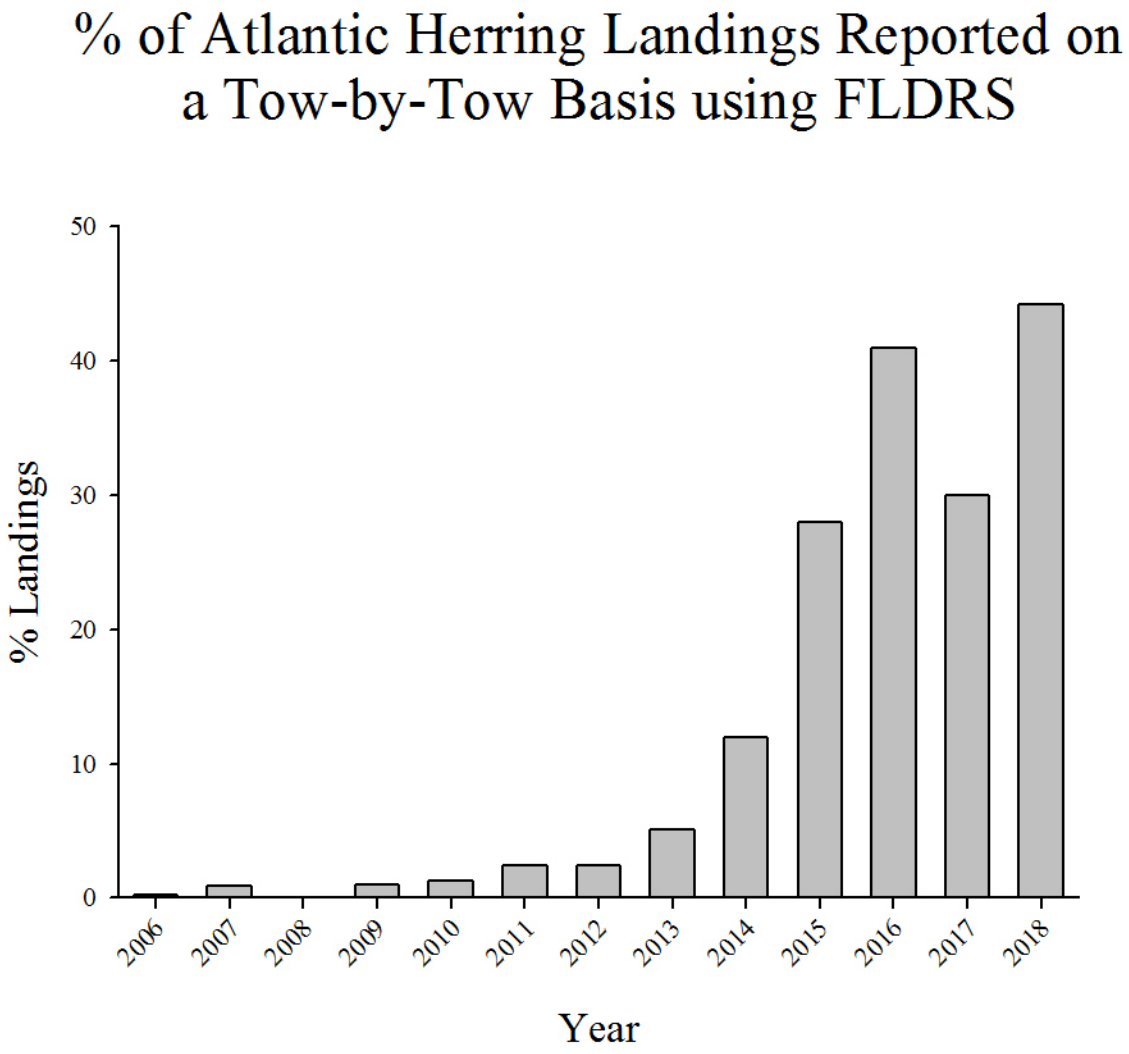

Figure 6: The percentage of Atlantic herring landings from vessels using FLDRS at the haul-by-haul level. The FVTR Apportion table was used to estimate catch and the CFDBS CFDERS tables were used to estimate landings.

References:

Palmer, Michael C., Wigley, Susan E., Hoey, John J., and Palmer, Joan E (2007) An Evaluation of the Northeast Region's Study Fleet pilot program and Electronic Logbook System: Phases I and II. NOAA Technical Memorandum NMFS-NE-204, 78 pp.

Appendix B7

Working Paper:

Maturity and spawning seasonality of Atlantic herring (*Clupea harengus*) in US waters: QA/QC of data collected from fishery dependent and independent sources, with an evaluation of the consequences of skipped or spring spawning for stock-recruit relationships and stock assessment

Mark J. Wuenschel and Jonathan J. Deroba

Introduction and Objective

Altantic herring (*Clupea harengus*) is of commercial importance throughout its range across the eastern and western north Atlantic. Over this broad geographic range, reproductive plasticity is evident; stock specific size and age at maturity, spawning seasonality, egg sizes, and spawning areas (Iles 1964, van Damme et al. 2009). In addition to the diversity of reproductive strategies, skip spawning (i.e. not all mature fish spawn in every year) has become increasingly apparent in several fish stocks (Rideout and Tomkiewicz 2011, Skjaeraasen 2009, Skjaeraasen 2012), and has been reported for herring in the eastern Atlantic (Engelhard and Heino, 2005, Kennedy et al., 2011, Bucholtz et al. 2013). Although recruitment in the western Atlantic is highly variable (Anthony and Fogarty 1985), a recent evaluation of spawning strategies in the region that considers the possibility of skipped spawning is lacking.

Commercial fishery catch samples from the third quarter of each year (July-September) have been used to define annual maturity ogives for input into Atlantic herring stock assessments (NEFSC 2012; Deroba 2015). During the 2015 Operational Assessment of Atlantic herring (Deroba 2015), systematic differences in the maturity-at-age of herring were found between commercial samples and NMFS fall bottom trawl survey samples, with the commercial samples generally having smaller proportions of herring mature-at-age than the survey, especially for age-3 (Figure 1). The commercial sample based age-3 maturity-at-age also had larger interannual variation than the survey samples. Exploratory analyses by length bins (across ages and for age-3) indicated a similar tendency towards lower proportions mature at length (especially for smaller sizes) in the commercial samples (Figure 2). These differences and the variation in age-3 maturity were a noteworthy uncertainty during the 2015 assessment because: 1) spawning stock biomass at maximum sustainable yield (SSB_{MSY}) varies with age-3 maturity at a constant F_{MSY}, 2) a relatively large year class was age-3 in 2014, the terminal year of the assessment, which contributed to a 2014 SSB that exceeded the SSB_{MSY} reference point by more than two-fold, and 3) the assessment estimates a stock-recruit curve that assumes maturity is known without error in the estimation of SSB each year. While none of these uncertainties or concerns were considered grounds to reject the assessment, incorrectly specifying maturity-at-age could lead to bias in MSY reference points, bias in annual estimates of stock and recruitment, and ultimately to incorrect conclusions about stock status and inappropriate management advice.

One possible source of the differences between the commercial and survey samples is that commercial samples are taken by a port sampler with the State of Maine while the survey samples are taken by NMFS. The State of Maine and NMFS use different maturity classification schemes (Table 1).

The accuracy of macroscopic based maturity determinations for Gulf of Maine and Georges Bank Atlantic herring from both the commercial port samples and fishery-independent samples has not been formally investigated. Inaccuracy of maturity staging of herring using macroscopic criteria has been reported elsewhere (McPherson et al. 2011). Oocyte development and maturity classification of herring based on microscopic characteristics has been documented in other areas (van Damme et al. 2009, McPherson et al. 2011, Kennedy et al., 2011, Bucholtz et al. 2013), but has yet to be applied in the NW Atlantic. In the Gulf of Maine and Georges Bank, Atlantic herring are considered to be fall spawners, with spring spawning reported but not quantified or considered in assessments. An understanding of oocyte development is necessary to determine skipped spawning, especially for 'resting' type (Rideout and Tomkiewicz 2011), which is further complicated by the possibility of spring or fall spawning in the region.

Gonad histology is considered the most accurate method for determining maturity. In addition to basic maturity information, histological methods can establish spawning seasonality. Preliminary work has suggested that not all herring spawn in the fall, and so may be either skip spawners or a spring spawning contingent. The occurrence of skip or spring spawning would suggest a violation of the current assumption of all fall spawners in the assessment, and could lead to biased estimates of SSB and reference points. Histological analysis of herring ovaries and the size frequency distributions of developing oocytes indicate whether an individual has spawned recently or is preparing to spawn in the near or more distant future (5-6 months). This information, along with prior studies of oocyte development for the species is used to identify whether apparent 'non-participatory' fish collected in fall are indeed skip spawners or if they spawn in a different season (spring).

In this study we apply histological (microscopic) methods to document oocyte development through the year for both spring and fall spawning herring. Using oocyte stages and other histological characters, we develop criteria to assign maturity stages, spawning seasonality, skipped spawning, and assess the accuracy of macroscopic maturity determinations from both commercial port samples and the fishery-independent surveys in Gulf of Maine and Georges Bank herring. Since the stock assessment of Atlantic herring assumes all mature fish spawn in fall, we then evaluate the implications of observed reproductive diversity on stock-recruit models and the stock assessment.

Methods

Oocyte development and histology-based maturity classification

We obtained gonad samples of Atlantic herring from multiple sources operating at different times of the year. Samples obtained from NEFSC spring and autumn bottom trawl surveys (SBTS and

ABTS, respectively) were processed at sea; maturity classified macroscopically following Burnett et al. 1989 (Table 1), fish weight and gonad weight (+/- 0.1 g). Samples obtained from the NEFSC Cooperative Research Program (Study Fleet) were held on ice and transported to the laboratory where they were processed; fish weight and gonad weight +/- 0.001g, otoliths removed for ageing. Gonad samples were also obtained from the Maine DNR sampling of the commercial catch. The Maine DNR samples were usually frozen (but were fresh in some cases), and processed in the laboratory; maturity classified macroscopically using a different scheme than NEFSC samples (Table 1), fish weight and gonad weight +/- 1 g. In all cases, after weighing the gonad, a small portion was preserved in 10% buffered formalin for histology. Preserved tissue samples were processed following standard protocols; dehydrated in ETOH, embedded in paraffin, thin sectioned and stained with Mallory's trichrome. Histology was viewed with a digital microscope (Nikon Coolscope II) and oocyte were staged following (Brown-Peterson et al., 2011). Additional microscopic characters were recorded; the thickness of the gonad wall, presence and stage of post ovulatory follicles, presence and stage of atresia (Figure 3). Diameters of oocytes (~ 60-80 per fish) sectioned through the nucleus were measured using image analysis (ImageJ) from non-overlapping images from histological sections of representative individuals from each month available. The histological characters and oocyte diameters (Figure 4) from all months sampled were used to develop classification algorithm to assign maturity stages and spawning seasonality (Table 2). The histology-based classifications were compared to macroscopic assessments at-sea for ABTS 2014, ABTS 2015, SBTS 2016, and 2015 Q3 commercial samples. The sampling protocol for histological samples collected on NEFSC surveys for verification was as follows; at each station, after determining maturation stage of individuals sampled for age and growth, one fish of each macroscopic maturity stage was selected for histology sampling until a total of 100 was reached. This protocol ensured histological samples covered all stages encountered, and came from a wide region. Similarly, 100 random histological samples were requested from the third quarter of 2015 sampled by the Maine DMR staff processing the commercial samples with the following objectives; to cover as broad a range in dates, areas, and macroscopic stages as possible, with a preference for fresh (not frozen) samples which produce higher quality histology.

QA/QC of macroscopic maturity estimation.

The accuracy of macroscopic maturity staging for Atlantic herring was assessed for NEFSC surveys (Fall 2014, 2015; spring 2016) and ME DNR (third quarter 2015). The NEFSC Northeast Cooperative Research Program (Study Fleet) collections were used to inform histological characters (oocyte stages, POF persistence) and oocyte size distributions in months not sampled from the other sources and were used solely in the development of classification algorithms (no comparison of macroscopic vs. histologic determinations were performed).

Estimation of spring and/or skipped spawning

Based on the histological characteristics and month of collection, we were able to assign spawning seasonality for mature and maturing fish. For immature fish that have not yet initiated secondary development of oocytes, it was not possible to identify spawning seasonality. The identification of skip spawners is limited to discrete portions of the year, and in the case of Atlantic herring this is further complicated by potential for spring or fall spawners. We established criteria that would indicate skip spawners based on the month of collection, oocyte stages, POFs and atresia (Table 2).

Stock-recruit modeling

Estimates of biomass and recruitment (age-1 abundance) from the 2015 stock assessment (Deroba 2015) were used to evaluate the effect of spring spawning or skipped spawning on estimates of

Beverton-Holt stock-recruit parameters. Beverton-Holt models were fit using three different definitions of spawning stock biomass (*SSB*) that corresponded to spring spawning, skipped spawning, or 100% fall spawning. For spring spawning, some fraction of the stock was assumed to have spawned in May, while the remainder of surviving fish spawned in October. The annual *SSB* related to recruitment in the following year was the sum of the spring and fall spawners:

$$SSB_{y,spr} = SSB_{y,Jan1} * p_s * \exp\left({}^{5}/_{12} * Z_y\right) + SSB_{y,Jan1} * p_f * \exp\left({}^{10}/_{12} * Z_y\right);$$

where $SSB_{y,spr}$ was spawning stock biomass in year *y* and *spr* denoted that the calculation included spring spawners, $SSB_{y,Jan1}$ was spawning stock biomass on January 1, p_s was the fraction of the stock that spawned in spring, $p_f = 1 - p_s$ was the fraction of the stock that spawned in fall, and Z was total instantaneous mortality:

$$Z_y = M + F_y;$$

where M was instantaneous natural mortality, and F was fully-selected instantaneous fishing mortality estimated for each year in the 2015 stock assessment (Deroba 2015). Skipped spawning $\left(SSB_{skip}\right)$ was approximated by not including the spring spawners in the calculation of the annual SSB:

$$SSB_{y,skip} = SSB_{y,Jan1} * p_f * \exp\left({}^{10}/_{12} * Z_y\right).$$

In this context, p_s equates to the proportion of the stock that skips spawning. Fall spawning $\left(SSB_{fall}\right)$, as assumed in recent stock assessments, was calculated as in skipped spawning except with $p_f = 1$:

$$SSB_{y,fall} = SSB_{y,Jan1} * \exp\left({}^{10}/_{12} * Z_y\right).$$

These methods for calculating SSB assumed the same maturity ogive applied in both seasons and ignored within year growth. A Beverton-Holt stock-recruit model was fit using each of the definitions for SSB:

$$R_{y+1} = \frac{\alpha * SSB_{y,x}}{\beta + SSB_{y,x}};$$

where x denoted one of the three definitions of SSB (*spr, skip, or fall*), R was estimated recruitment from 1966-2013 from the 2015 stock assessment (Deroba 2015), and α and β were parameters. This method assumed that the expected recruitment at a given level of SSB was the same in both seasons (i.e., spring spawners were the "same" as fall spawners).

Models were fit using a range of M and $p_s\ (p_f)$ values (Table 3). The mean stock-recruit curve from each fit was plotted, and plots were qualitatively examined for differences.

Sensitivity of the stock assessment

The stock assessment was evaluated for sensitivity to spring spawning and skipped spawning. With the exception of modifying the SSB calculation, all inputs and settings were identical to the 2015 stock assessment (Deroba 2015). The calculation of SSB in the stock assessment was modified as in the case of spring spawning $(SSB_{y,spr})$ and skipped spawning $(SSB_{y,skip})$ in the stock-recruit modeling methods, but the distinction in this case was that the estimation of the stock-recruit relationship was done internal to the assessment model and estimated with all the other associated parameters. Models were fit using a range of $p_s\ (p_f)$ values (Table 3). Time series plots of estimates of SSB, recruitment, and fully-selected fishing mortality were qualitatively examined for differences between the assessment modified for spring or skipped spawning and the 2015 assessment. Values of estimated steepness and unexploited SSB were also compared.

Results and Discussion

Using microscopic verification we found the macroscopic method to be reasonably accurate for Atlantic herring (direct agreement 60-87%), however errors in determination of sex (2-7%) and maturity (0-13%) were evident in all surveys (Tables 4-8). Errors in maturity were highest in the spring survey period. Subtle disagreements (not affecting maturity) between the histologic and macroscopic methods were also evident in all surveys. During spring, many fish classified as resting at sea were undergoing early development which was only visible via histology.

Misclassification of sex occurred in all surveys (summarized in Table 8). Most of these misclassifications occurred for immature fish, where it is more difficult to differentiate sex macroscopically. Additionally, for most individuals during the spring survey period, the gonads are very small, making it more difficult to distinguish males from females macroscopically. This likely led to the higher rates of incorrect maturity in the spring (Table 6), and supports the continued estimation of maturity from samples obtained closest to the main spawning season in fall. The results from the spring also indicate histology was able to identify early developing fish before this was evident macroscopically (ED fish classified as resting at sea). This is not surprising since the characters that define early developing are not readily visible with the naked eye. Several late developing and one spent fish were collected in the spring, a clear indication of spring-early summer spawning. Interestingly, the spent fish was classified as ripe and running at sea. This individual contained advanced and mature oocytes that histology indicated were 'residual' (i.e. left over). During winter and spring, the difference in ovary condition between spring and fall spawners is obvious (Figures 5 and 6). Therefore, the estimation of spring spawning from developing and spawning active herring in the spring is considered reliable. Nonetheless, spring spawning was relatively rare (2.5-13%, Table 8). A summary herring maturity from the SBTS time series across regions (Figure 7) indicates a latitudinal trend in the proportion of spring spawning herring (pre-spawning and spawning) encountered. Proportions of spring spawning increased with latitude; 0-10% in the Middle Atlantic Bight, 5-20% on Georges Bank, 10-40% in the Gulf of Maine, and 10-80% on the Scotian Shelf. Although rates of spring spawning were higher on the Scotian Shelf, fewer fish were sampled in that region.

Because of the sampling scheme used, wherein samples were requested across stages, and not in proportion to the stages encountered, the error rates reported here do not depict actual error rates.

To arrive at overall errors in macroscopic classifications in the surveys, one would need to apply stage specific error rates to all fish examined in the surveys. In fall most herring are developing, which is sometimes confused with resting (regenerating), but was never confused with immature. Therefore, proportionally more developing fish in fall would dilute the effect of errors in the rarer stages (i.e. resting), reducing the overall error rate. In a similar vein, although error rates in spring were higher, the late developing and spawning active females were accurately identified, confirming spring spawning in the region. The commercial Q3 collection was the most precise (Table 8), possibly due to being performed by a single experienced technician. In contrast, the NEFSC survey data is collected by multiple individuals per survey, with varying backgrounds and experience levels with respect to herring maturity. Annual training workshops on fish maturity are held at the NEFSC to address this potential source of error.

The spatial distribution of samples from the NEFSC surveys differed from the Q3 commercial samples analyzed by the Maine DNR which were predominately from inshore stat areas (512, 513, 514; Figure 8). Most immature fish remain inshore in fall (i.e. do not undergo spawning migrations offshore), so samples inshore will have more immature fish (overall and at a given age). This is illustrated in maps showing the spatial distribution in age 2 and 3 fish in 2014 and 2015 (Figs 9 and 10). The proportion mature at age 2 and 3 varies in the time series (Deroba 2015), but it appears immature individuals are found closer to shore in fall. In spring Atlantic herring are more widely distributed, including immature individuals (Figure 11). The spatial difference in maturity likely contributes to observed differences in estimated proportions mature at age from survey and commercial data sources in fall. When analysis of survey data is constrained to inshore regions, the differences in maturity decrease (Figure 12).

Stock-recruit modeling

The fits of stock-recruit models with spring spawning and fall spawning were generally similar, but skipped spawning produced higher recruitment at a given level of SSB (Figure 13). Natural mortality had a negligible effect on the fits, especially relative to the fraction of the stock that skipped spawning (p_s in the context of skipped spawning). At low levels of skipped spawning, differences among all fits were generally similar, but the skipped spawning stock-recruit relationships became more distinct at higher levels of skipped spawning (Figure 13).

Sensitivity of the stock assessment

Results for spring spawning were insensitive to the value of p_s, and so only results for $p_s = 0.3$ were reported here. Time series plots were generally similar between the assessment model with spring spawning and the 2015 assessment (Figure 14). Estimates of steepness and unfished SSB were also similar (Table 9). In the case of skipped spawning, differences in the time series plots with the 2015 assessment were only evident for SSB, and SSB was less than the 2015 assessment (Figure 14). The degree of difference increased with the value of p_s, but only results with $p_s = 0.3$ were reported for simplicity (Figure 14). Estimated steepness with skipped spawning was similar to the 2015 assessment, but unfished SSB was less (Table 9). Skipped spawning seems to scale SSB and related reference points, with little other consequences.

This analysis could be improved by accounting for in-season growth and different maturity ogives between seasons. The methods assumed, however, that the maturity and weight-at-age matrices from the fall spawning season also applied in the spring. Spring spawners are less likely to be mature-at-age and have smaller weights-at-age than fall spawners. Consequently, this analysis falsely inflated the contribution that spring spawners would have, and so accounting for these seasonal differences would likely only result in reducing any differences already observed among model fits.

The differences in the stock-recruit modeling between assuming spring spawning or skipped spawning serve to demonstrate the consequence of falsely concluding one mechanism or the other. Results suggest, however, that making such a false conclusion would be of little consequence until the fraction of spring or skipped spawners was relatively high, at which point other indications of spring or skipped spawning would likely become evident in survey or commercial catch samples.

At the levels of possible spring or skipped spawning reported here, the effect on the stock assessment can likely be ignored. Levels of measurement error, process error, and other structural uncertainty also likely far exceed the uncertainty induced by spring or skipped spawning suggested by this analysis, which also supports the conclusion that the effect of spring or skipped spawning can be ignored.

Conclusions

Histological analysis of herring gonads from multiple sources, and inclusion of reproductive diversity in the stock assessment indicated the following:

- error rates of the macroscopic method to determine maturity were low
- there were not any systematic biases between NEFSC and ME DNR maturity methods
- spring spawning was confirmed at low levels
- skipped spawning was not observed
- the spatial distribution of immature herring differs from that of mature herring in fall
- differences in maturity estimated from NEFSC survey and Q3 commercial are likely due to spatial heterogeneity of the population with respect to maturity
- skipped spawning scales SSB and related reference points, with little other consequences
- incorporating observed rates of spring and/or skip spawning had little effect on the stock assessment

Acknowledgments

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Table 1. Macroscopic and histological maturity classification schemes used in NEFSC surveys (Table 11 in Burnett et al. 1989) and ME DNR sampling of commercial catch (Table 3B in Burnett et al. 1989). Corresponding histological classes are listed (following Brown-Peterson et al. 2011, with potential skip spawning following Rideout et al. 2005); in some cases multiple stages in one scheme are represented by a single stage in another scheme.

Macroscopic Classes NEFSC	**Macroscopic Classes ME DNR**	**Histological Classes**
Immature	I (Immature) II (Immature will spawn next season)	Immature Immature First Maturing
Developing	III (Ripening, Early stage) IV (Ripening mid stage)	Early Developing Late Developing Spawning Capable Skip Spawning (Reabsorbing)
Ripe Running Ripe	V (Ripe) VI (Spawning)	Spawning Active
Spent	VII (Spent)	Regressing
Resting	VIII (Resting)	Regenerating Skip Spawning (Resting)

Table 2. Microscopic characteristics for each histological maturity stage.

Histological Classes	**Characteristics**
Immature	Ovaries small with thin ovarian wall and little space between oocytes; only oogonia and PG oocytes present
Immature First Maturing	PG, CA, oocytes present with thin ovarian wall.
Early Developing (repeat)	Ovaries with PG, CA; thick ovarian wall and/or late stage POFs indicating prior spawning.
Late Developing	Enlarging ovaries with Vtg1, Vtg2 oocytes.
Spawning Capable	Large ovaries with Vtg3 oocytes present. Atresia of vitellogenic oocytes may be present. Early stages of OM can be present.
Skip Spawning (Reabsorbing)	Mass atresia of vitellogentic oocytes.
Spawning Active	Oocytes undergoing late GVM, GVBD, hydration, or ovulation.
Regressing	Flaccid ovaries with thick ovarian wall; atresia and recent POFs present. Most advanced oocyte stage is primary growth, with some residual secondary or tertiary growth oocytes possible.
Regenerating	Small ovaries with thick ovarian wall. Late stage atresia or POFs may be present. Only oogonia and PG oocytes present.
Skip Spawning (Resting)	Small ovaries with thick ovarian wall. Only oogonia or PG oocytes present. No indication of participation in proximal spawning season; no secondary or tertiary growth oocytes, recent POFs, or atresia.

Table 3. Range of natural mortality (M) and proportion of spring (p_s) and fall (p_f) spawners evaluated.

M	p_s	p_f
0.20	0.10	0.90
0.35	0.20	0.80
0.50	0.30	0.70

Table 4. QA/QC results for the 2014 fall bottom trawl survey (2015ABTS). In fall IFM fish are not expected to spawn until the following calendar year, so they should not be included in SSB (i.e. not mature). Green cells indicate direct agreement, red cells indicate incorrect maturity.

	Immature	Developing	Ripe	Ripe & Running	Spent	Resting
Immature	8	0	0	0	0	3
Immature First Developing	0	0	0	0	0	0
Early Developing	0	1	0	0	0	2
Late Developing	0	7	6	0	0	0
Spawning Capable	0	1	2	0	0	0
Spawning Active	0	0	0	0	0	0
Regressing	0	1	2	0	0	3
Regenerating	0	4	1	0	0	51
Skip Spawner	0	0	0	0	0	0

Table 5. QA/QC results for the 2015 fall bottom trawl survey (2015ABTS). In fall IFM fish are not expected to spawn until the following calendar year, so they should not be included in SSB (i.e. not mature). Green cells indicate direct agreement, red cells indicate incorrect maturity.

	Immature	Developing	Ripe	Ripe & Running	Spent	Resting
Immature	7	0	0	0	0	0
Immature First Developing	1	0	0	0	0	1
Early Developing	0	0	0	0	0	2
Late Developing	0	14	2	0	0	0
Spawning Capable	0	1	2	0	0	0
Spawning Active	0	0	0	0	0	0
Regressing	0	2	1	0	0	3
Regenerating	3	1	0	1	1	46
Skip Spawner	0	0	0	0	0	0

Table 6. QA/QC results for the 2015 Q3 commercial samples (ME2015 Q3). In fall IFM fish are not expected to spawn until the following calendar year, so they should not be included in SSB (i.e. not mature). Green cells indicate direct agreement, red cells indicate incorrect maturity.

	I	II	III	IV	V	VI	VII	VIII
Immature	2	1	0	0	0	0	0	0
Immature First Developing	0	2	0	0	0	0	0	0
Early Developing	0	2	10	0	0	0	0	0
Late Developing	0	0	34	10	0	1	0	0
Spawning Capable	0	0	1	2	10	7	0	0
Spawning Active	0	0	0	0	0	5	0	0
Regressing	0	0	0	0	0	0	4	0
Regenerating	0	0	0	0	0	0	0	7
Skip Spawner	0	0	0	0	0	0	0	0

Table 7. QA/QC results for the 2016 Spring bottom trawl survey (2016SBTS). In the spring, IFM fish would be expected to spawn in the calendar year (that fall) so they should be included in SSB (i.e. not immature). Green cells indicate direct agreement, red cells indicate incorrect maturity.

	Immature	Developing	Ripe	Ripe & Running	Spent	Resting
Immature	1	0	0	0	0	1
Immature First Developing	5	0	0	0	0	0
Early Developing	4	4	0	0	0	24
Late Developing	0	7	2	0	0	0
Spawning Capable	0	0	0	0	0	0
Spawning Active	0	0	0	0	0	0
Regressing	0	0	0	1	0	0
Regenerating	3	3	0	0	0	40
Skip Spawner	0	0	0	0	0	0

Table 8. Summary of sex and spawning group determinations for the four data sources. For Males the percentages listed in parentheses are the percentage males incorrectly classified as females macroscopically. For females, the percentages listed in parentheses are the percentage of mature females in that spawn group. The direct agreement is the sum of the diagonal green cells for survey (Tables 3-6), and the incorrect maturity is the sum of the red cells in each table. Percentages included for QA/QC are calculated for females only.

Sex	Spawn group	2014 (ABTS)	2015 (ABTS)	ME2015 (Q3)	2016 (SBTS)
Males (incorrect sex)		7 (7.0%)	4 (4.3%)	2 (2.0%)	5 (5.0%)
Females		93 (88.6%)	89 (95.7%)	98 (98.0%)	95 (95.0%)
Mature	Spring	3 (3.7%)	2 (2.5%)	12 (13.0%)	10 (11.4%)
	Fall	78 (96.3%)	77 (97.5%)	81 (87.0%)	78 (88.6%)
	Skip	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Immature	Unknown	11	9	5	7
QA/QC	Direct agreement	68 (73.1%)	69 (77.5%)	85 (86.7%)	57 (60%)
	Incorrect Maturity	3 (3.2%)	3 (3.4%)	0 (0%)	13 (13.6%)

Table 9.—Estimates of unfished spawning stock biomass and steepness from assessment with all fall spawning and 30% spring spawning.

	Fall Spawn Only (2015 Assessment)	With Spring Spawning	Skip Spawning
Unfished SSB	845176	885784	591623
Steepness	0.44	0.43	0.44

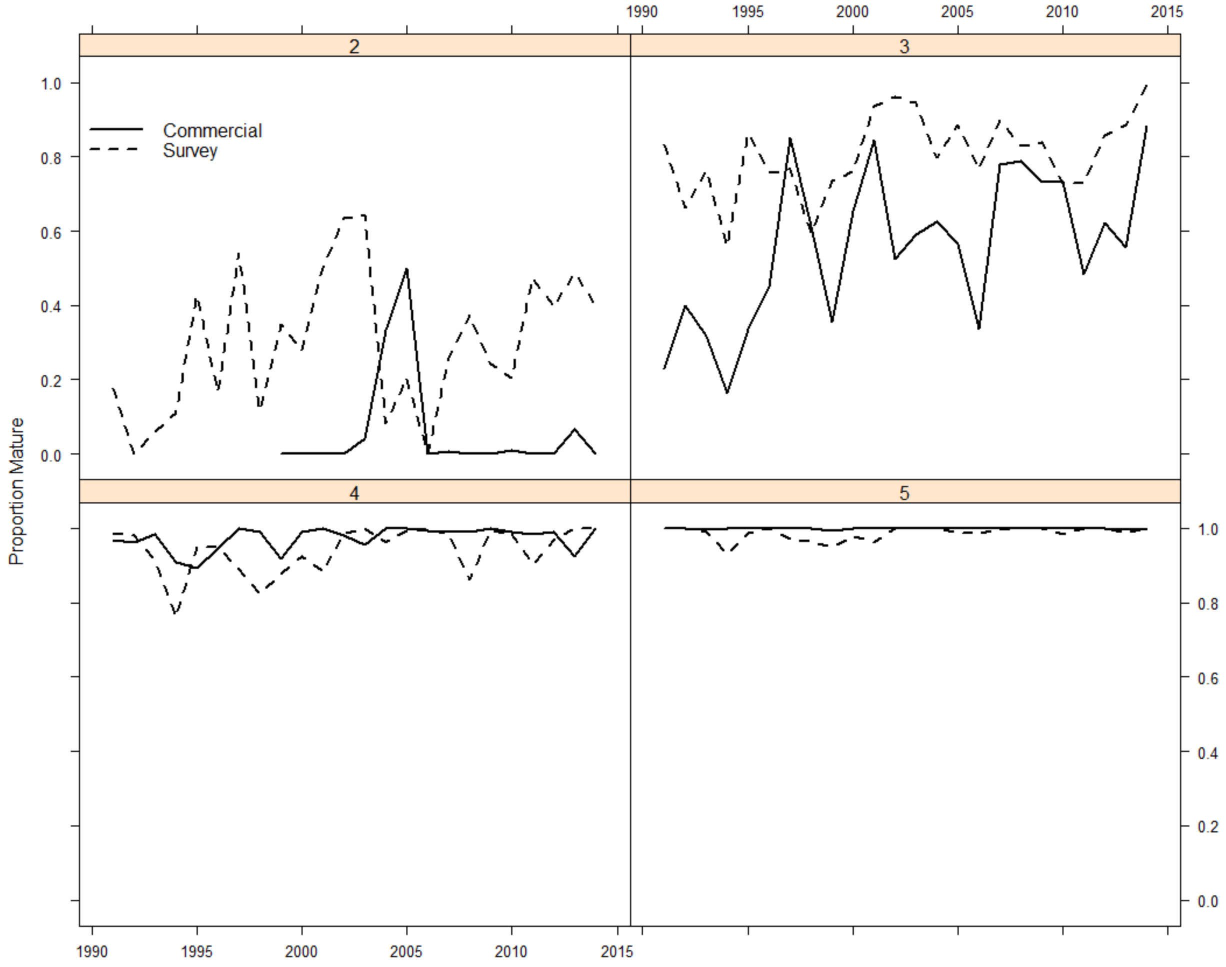
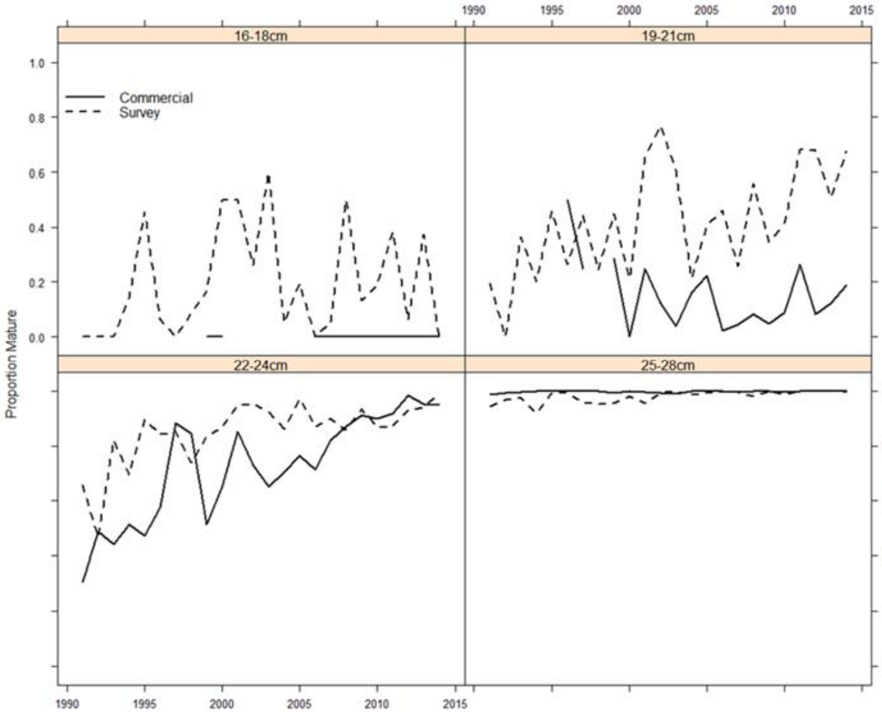


Figure 1. Proportion mature at age (age specified in the "strip" of each panel) from quarter three commercial fishery herring samples and the NMFS fall survey.



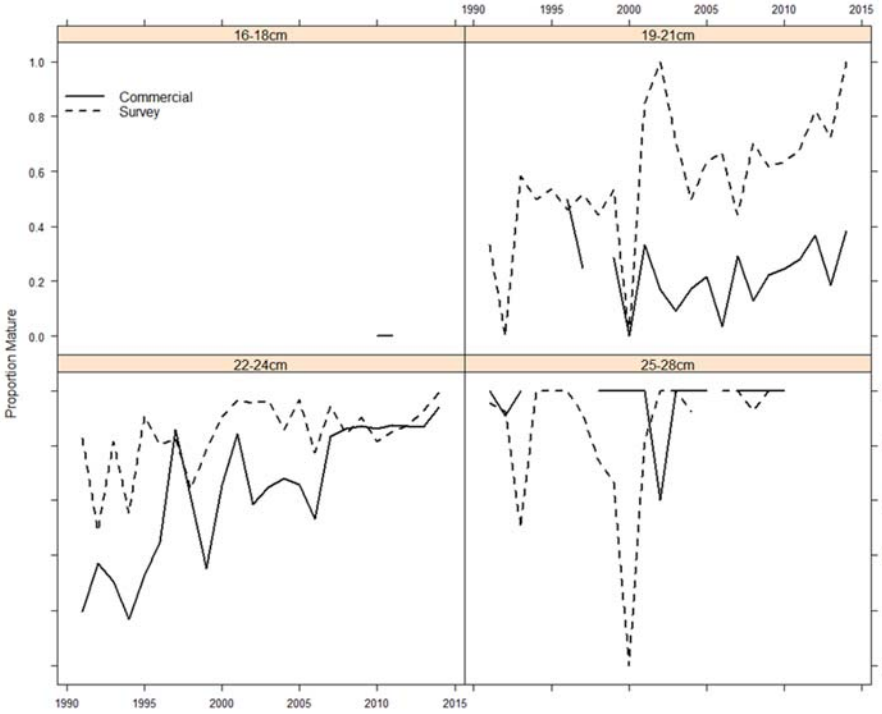


Figure 2. Proportion mature at length (length specified in the “strip” of each panel) for all ages (top) and age-3 (bottom) from quarter three commercial fishery herring samples and the NMFS fall survey.

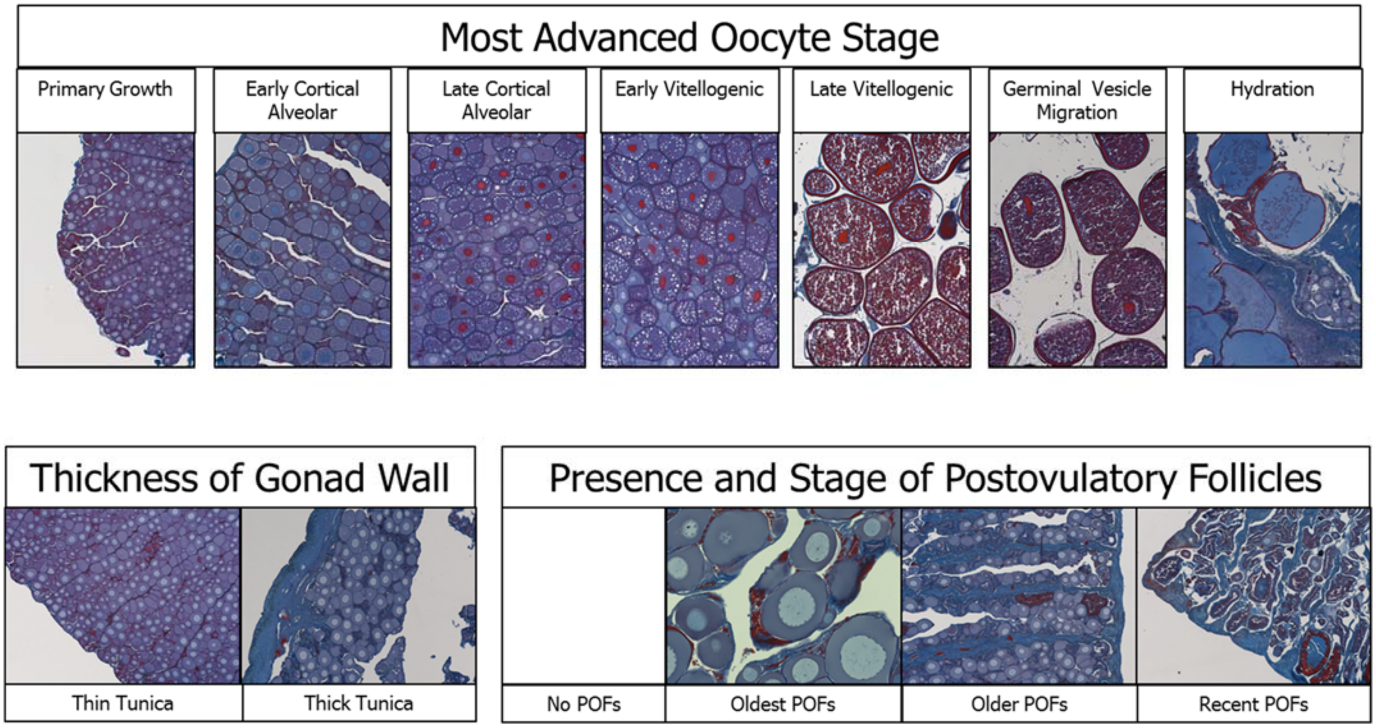


Figure 3. Histological criteria used to assess maturity of Atlantic herring. All images are at the same magnification, except for the 'Oldest POF' which is at a higher magnification.

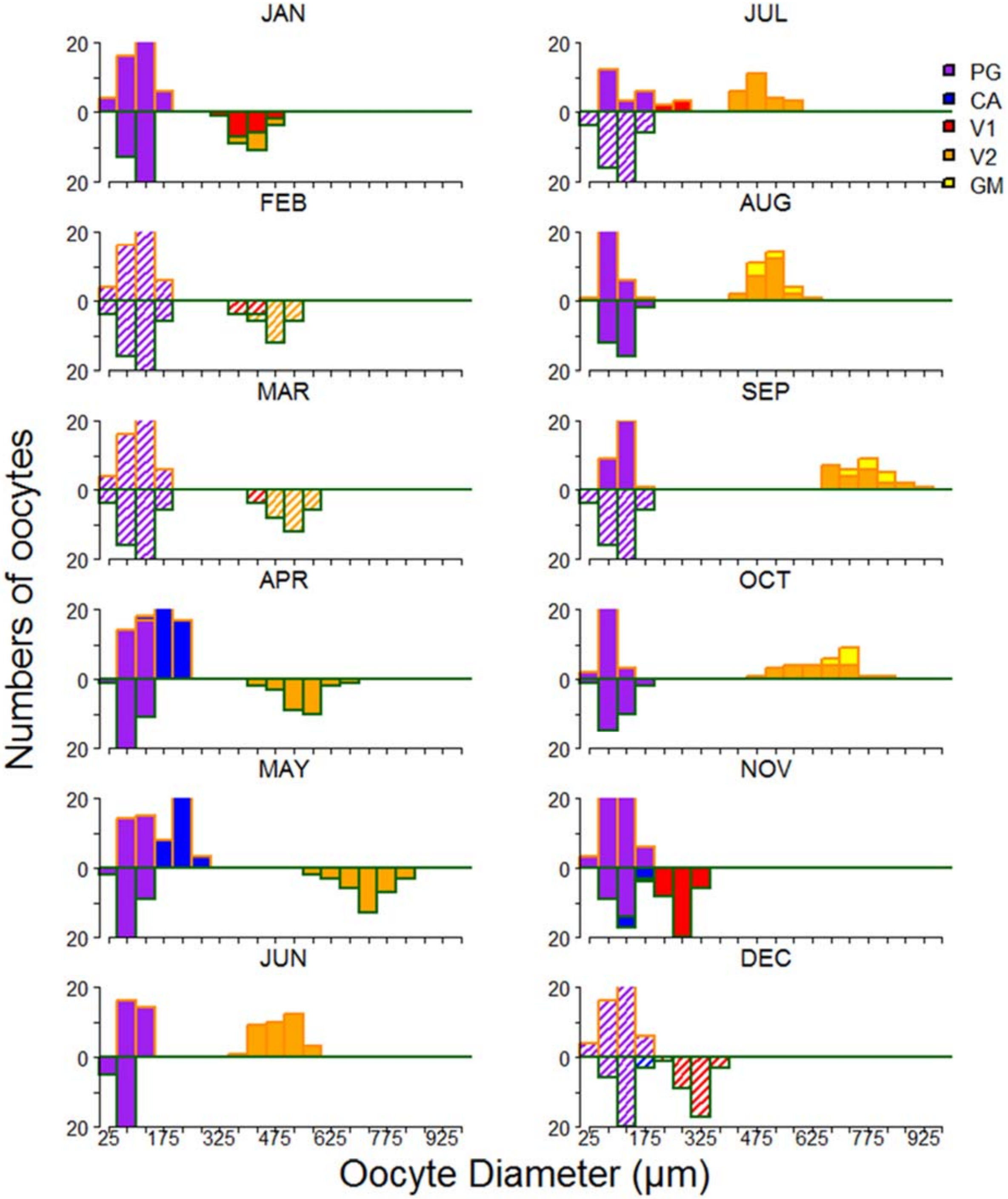


Figure 4. Monthly oocyte size distributions for representative Atlantic Herring (solid bars) or estimated from adjacent months and observed oocyte growth rates (shaded bars). Within each month, the distribution on top represents a fall spawner, and that on the bottom a spring spawner. PG, Primary Growth; CA, Cortical Alveolar; V1, Early Vitellogenic; V2, Late Vitellogenic; GM, Germinal Vesicle Migration.

Figure 5. Photographs of herring sampled January 22, 2015 from commercial catch (NEFSC Study Fleet). Top, resting female (Fall spawner); bottom, developing female (Spring spawner).

Figure 6. Herring photographed April 25, 2017 during the NEFSC spring bottom trawl survey. Top, resting female (Fall spawner); Bottom, developing female (Spring spawner).

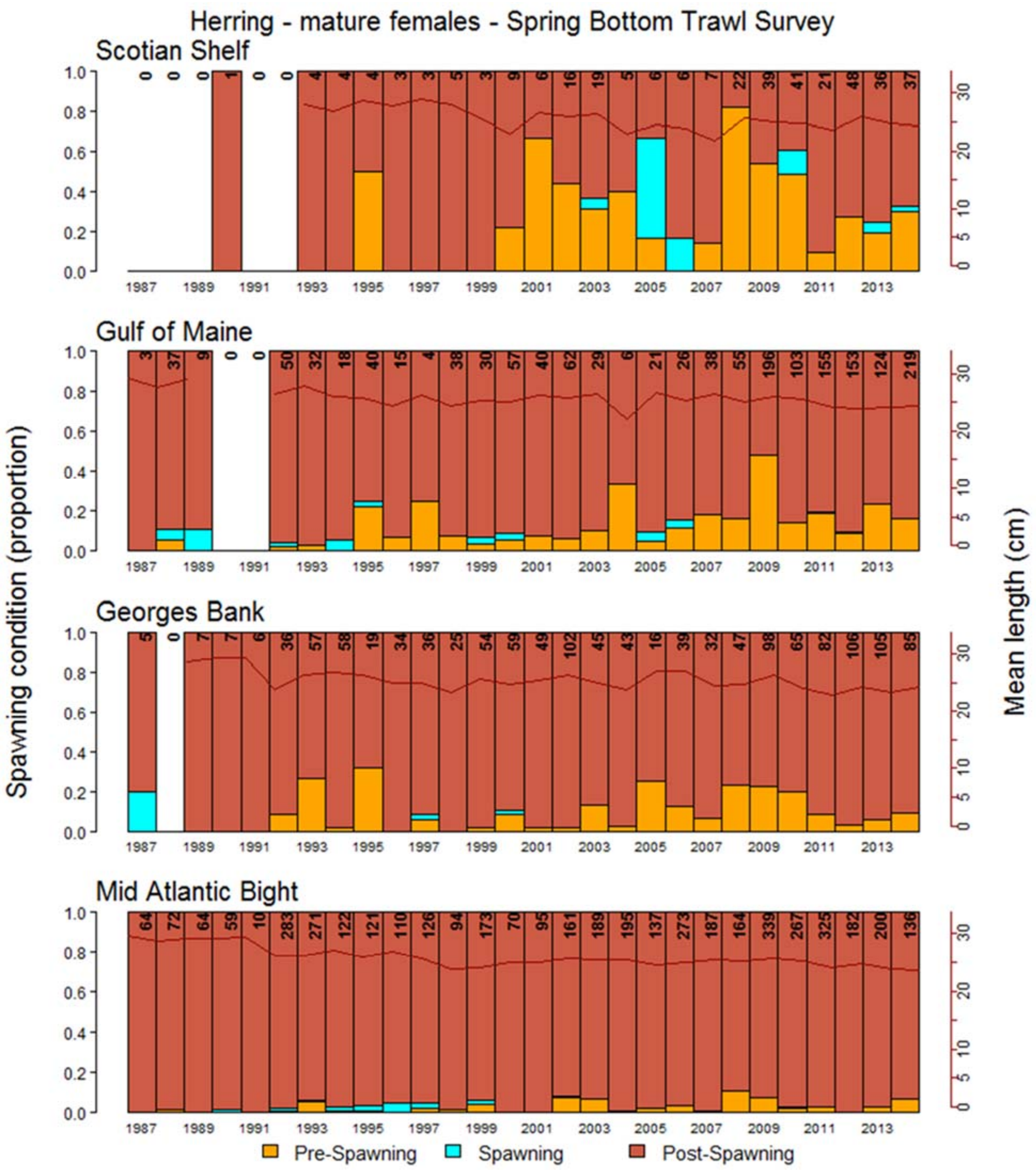
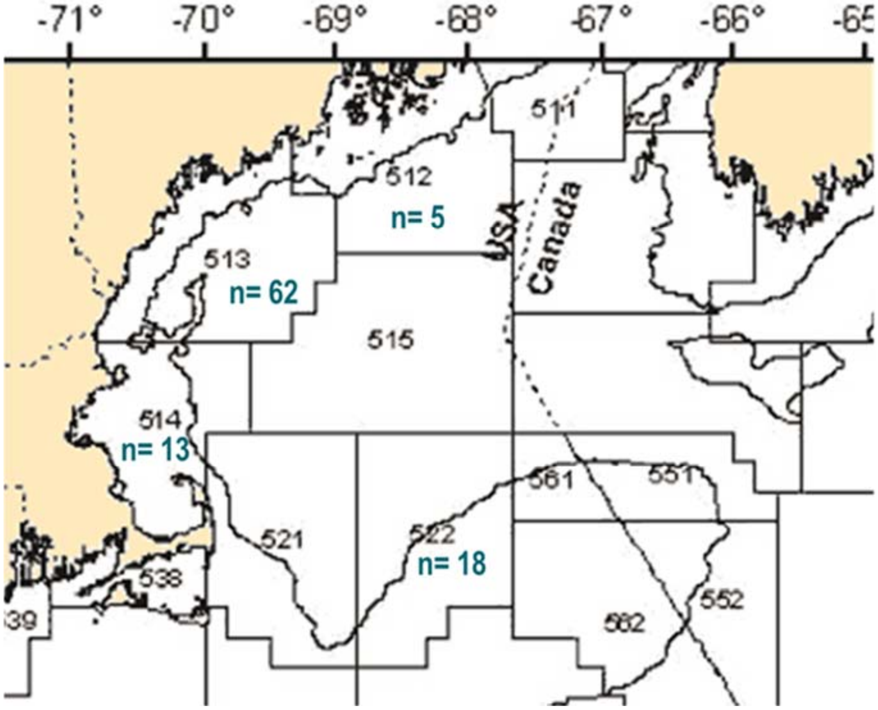


Figure 7. Time series of mature female macroscopic maturity collected on the NEFSC spring bottom trawl survey. For simplification, maturity classes are aggregated to illustrate spawning seasonality (Pre-Spawning = Developing, Spawning = Ripe and Ripe and Running, Post-Spawning = Spent and Resting). Pre-Spawning and Spawning groups represent spring spawning herring.



Stat Area	Sample size
512	5
513	62
514	13
522	18

Figure 8. Distribution and summary of female herring from Q3 commercial that were analyzed histologically.

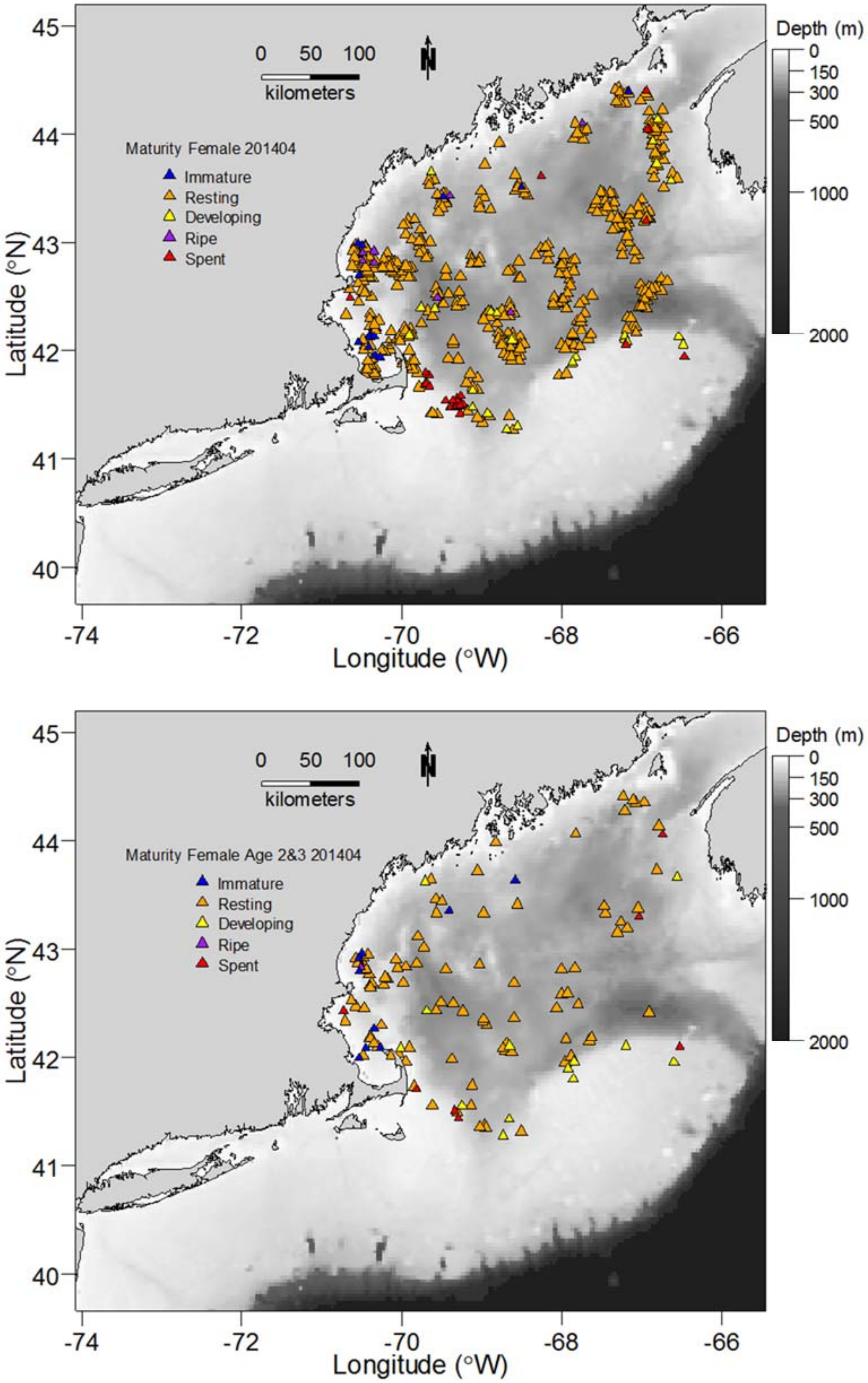
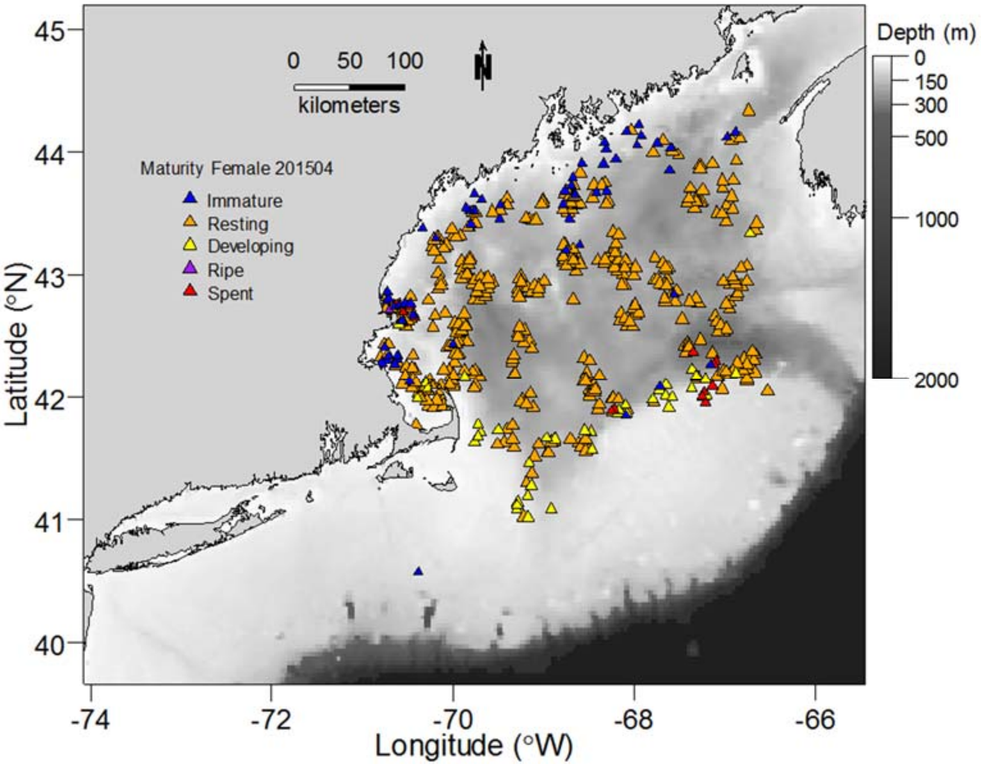
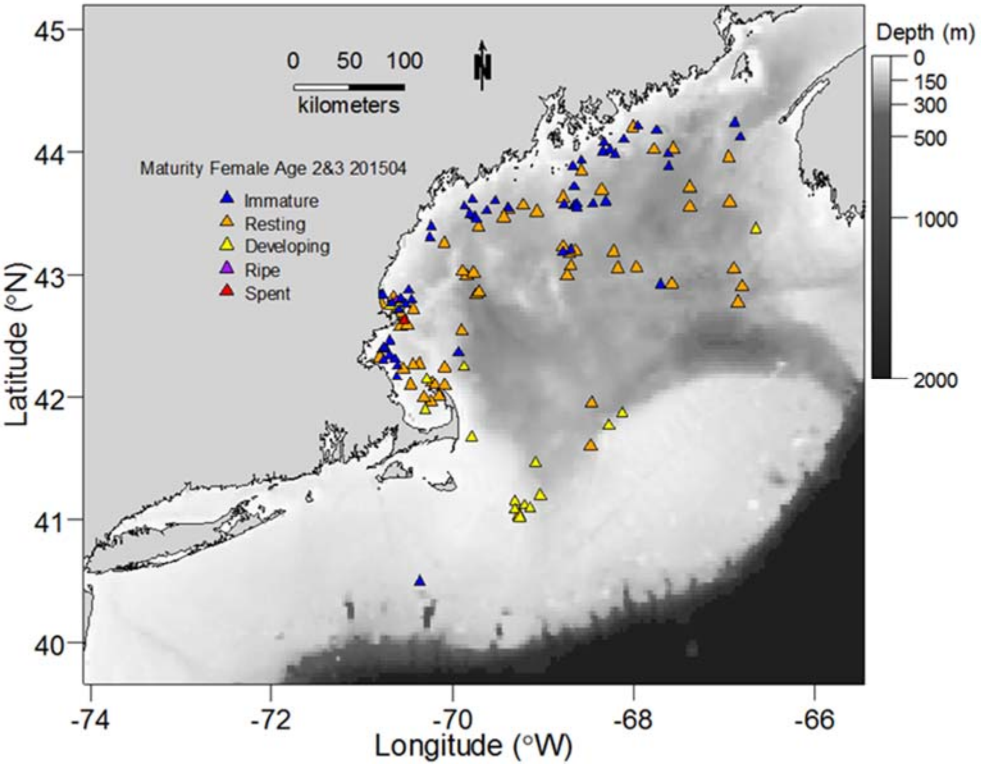


Figure 9. Distribution of all (top) and age 2 and 3 (bottom) females sampled for age, growth and maturity on the 2014 NEFSC fall bottom trawl survey. Points are jittered to reduce over-plotting.



Maturity Female 201504
▲ Immature
▲ Resting
▲ Developing
▲ Ripe
▲ Spent
0 50 100
kilometers
N
Depth (m)
0
150
300
500
1000
2000
45
44
43
42
41
40
Latitude (°N)
-74
-72
-70
-68
-66
Longitude (°W)



Maturity Female Age 2&3 201504
▲ Immature
▲ Resting
▲ Developing
▲ Ripe
▲ Spent
0 50 100
kilometers
N
Depth (m)
0
150
300
500
1000
2000
45
44
43
42
41
40
Latitude (°N)
-74
-72
-70
-68
-66
Longitude (°W)

Figure 10. Distribution of all (top) and age 2 and 3 (bottom) females sampled for age, growth and maturity on the 2015 NEFSC fall bottom trawl survey. Points are jittered to reduce over-plotting.

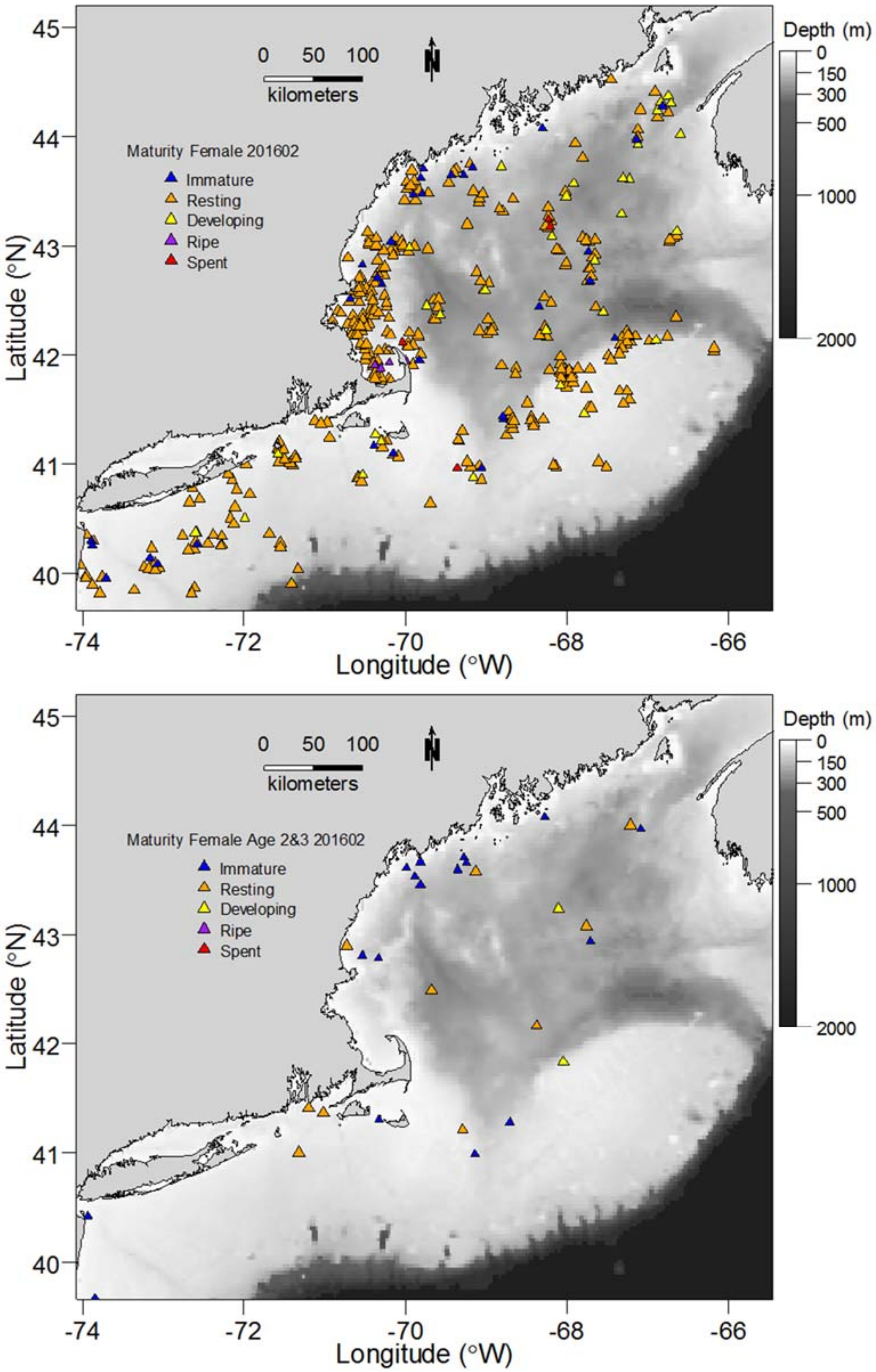


Figure 11. Distribution of all (top) and age 2 and 3 (bottom) females sampled for age, growth and maturity on the 2016 NEFSC spring bottom trawl survey. Points are jittered to reduce over-plotting.

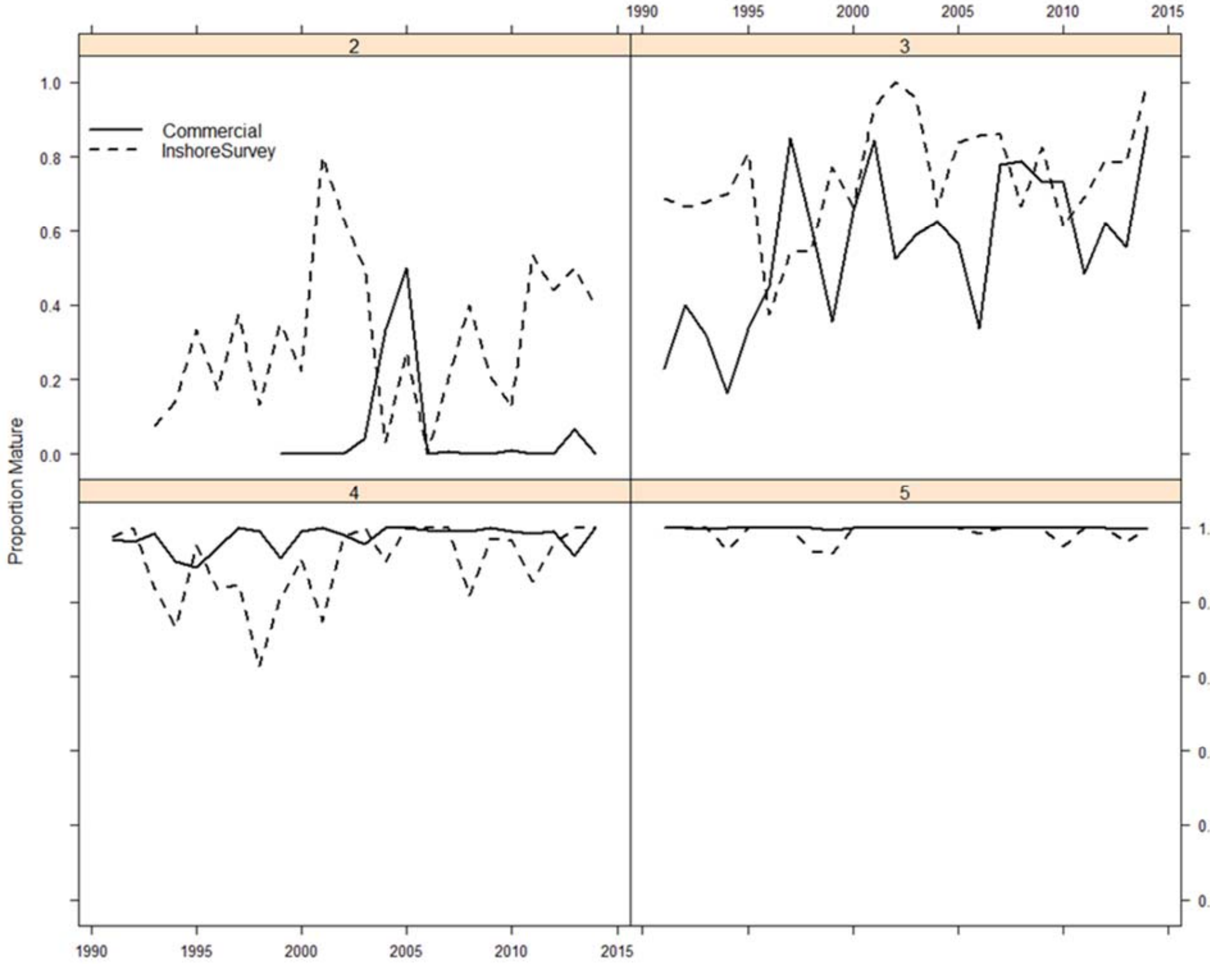


Figure 12. Proportion mature at age (age specified in the “strip” of each panel) from quarter three commercial fishery herring samples and the inshore strata (strata 26-27, 37-40) of the NMFS fall survey.

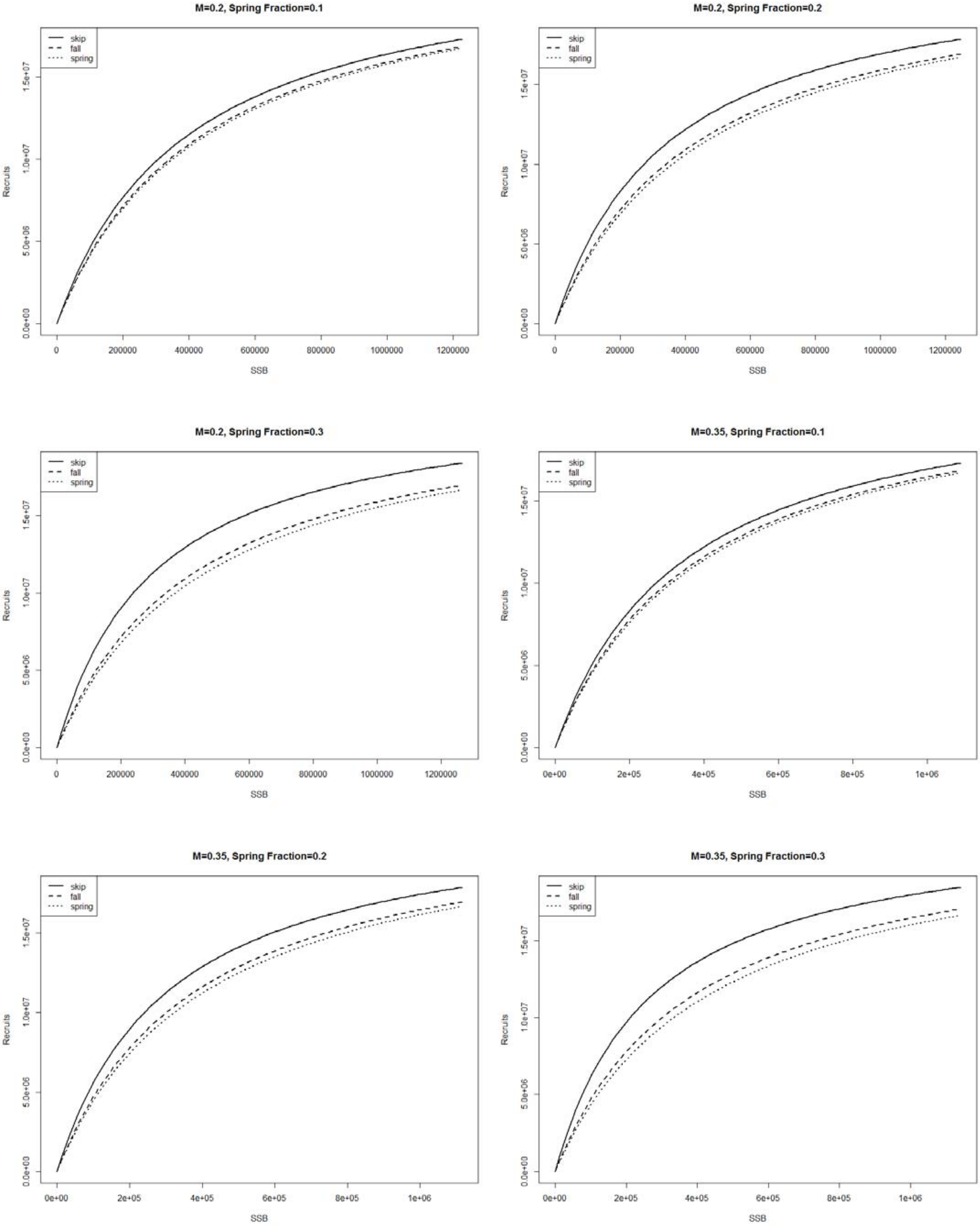
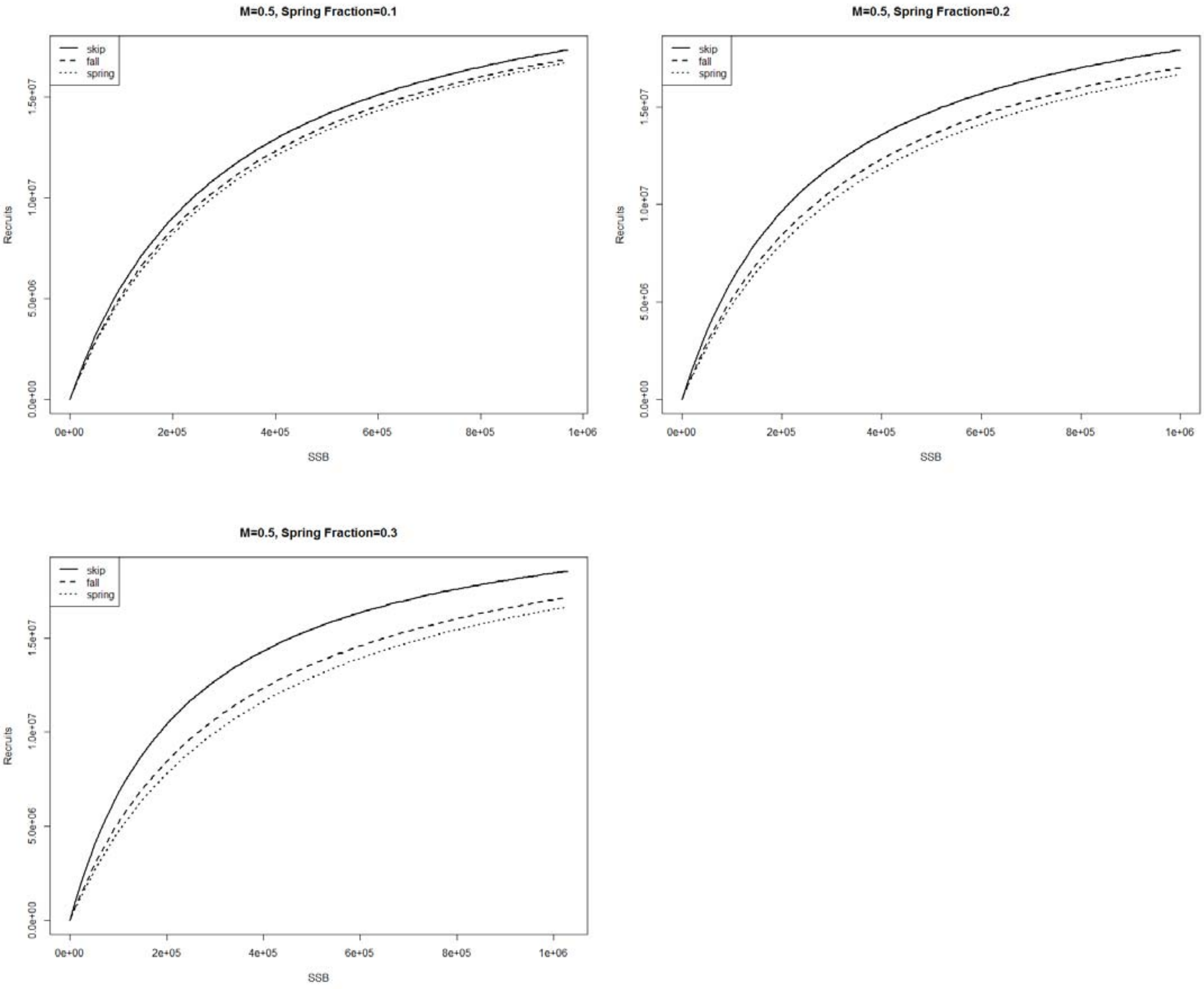
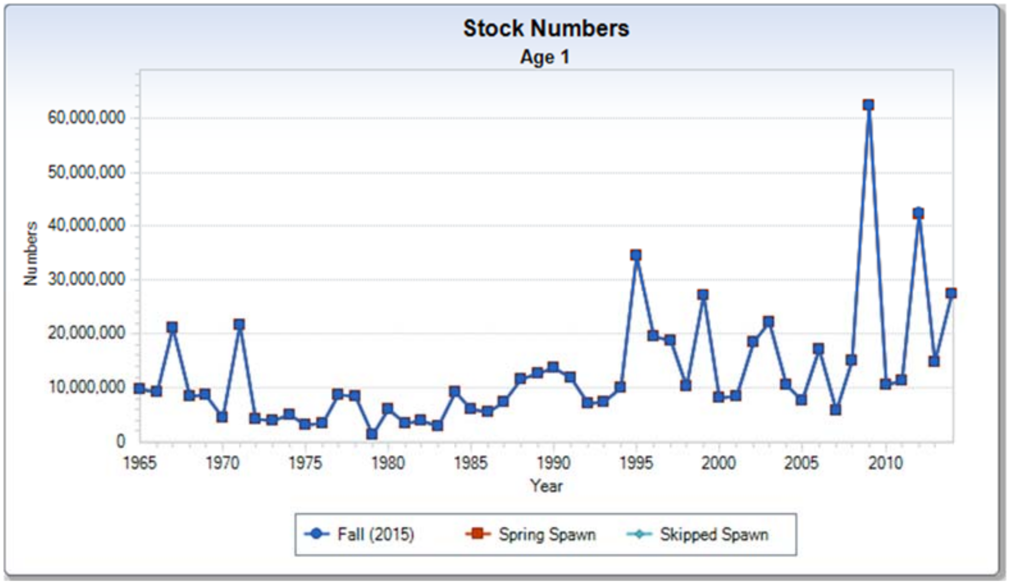


Figure 13.—Beverton-Holt stock-recruit model fits.

Figure 13. (continued)—





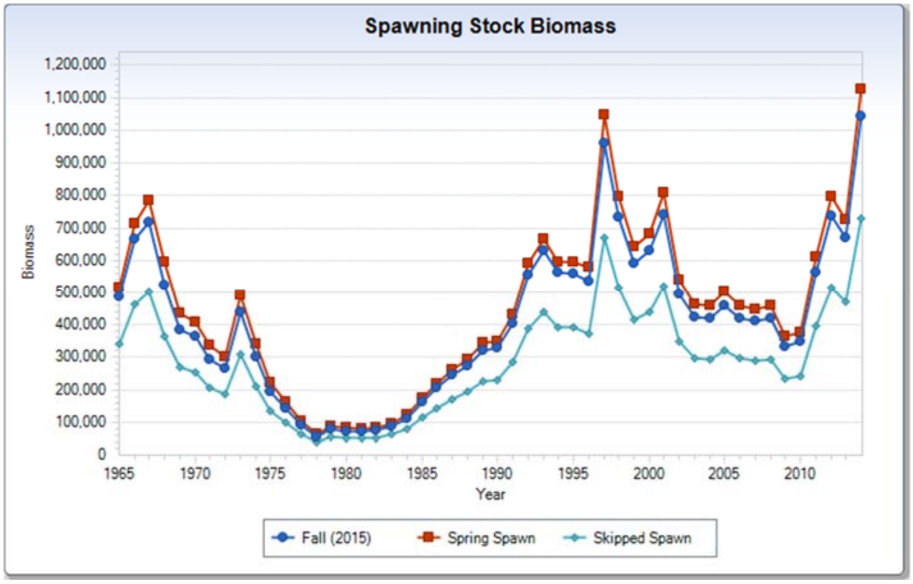


Figure 14.—Time series estimates from stock assessment models assuming all fall spawning and 30% spring or skipped spawning.

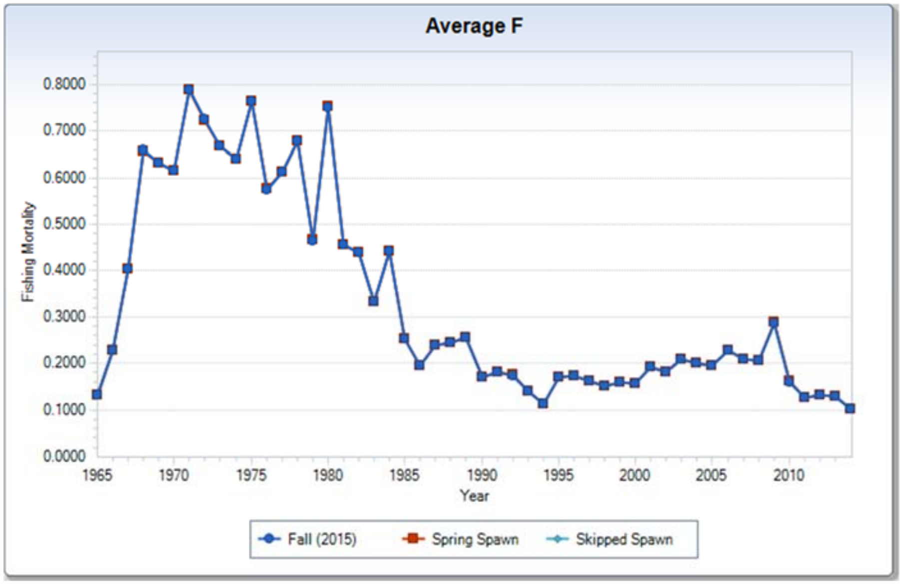


Figure 14.continued.

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Portland, ME 04101

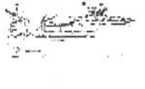
July 30, 2018

Robert E. Beal
Executive Director
ASMFC
1050 N. Highland Street, Suite 200A-N
Arlington, VA 22201

Robert E. Beal,

We agree with the NEFMC's recommendation to NOAA on the 2018 Sub-Annual Catch limits and to initiate action on the herring specifications for 2019-21. Hopefully, we can mitigate the effect of the possibility of a significant quota reduction. We believe that adjusting the allocation percentages for management areas is the best course of action. Area 1a should be allocated a higher percentage. This allocation would better the herring industry's market and be more beneficial to the Maine lobster industry.

Sincerely,

John-Paul Bilodeau
Regulations and Compliance

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